NASA Contractor Report 4783

Test Report—Direct and Indirect Lightning Effects on Composite Materials

R.W. Evans

Prepared for Marshall Space Flight Center
under Contract NAS8-39983
and sponsored by
the Space Environments and Effects Program
managed by the Marshall Space Flight Center

July 1997

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R.W. Evans
Tec-Masters, Inc. • Huntsville, AL

National Aeronautics and Space Administration
Marshall Space Flight Center • MSFC, Alabama 35812

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FOREWORD

This report describes lightning tests performed on composite material samples as a part of an investigation of electromagnetic effects on composite materials. This work was funded by NASA's Space Environments and Effects Program through the Electromagnetics and Aerospace Environments Branch of the Marshall Space Flight Center.

Mr. Steven D. Pearson, the Space Environments and Effects Program Manager, was the Technical Monitor for this contract effort (NAS8-39983). He was assisted by Mr. Matthew B. McCollum. From Tec-Masters, Inc., Mr. Dennis W. Camp was the Principal Monitor and Mr. Ross W. Evans was the Principal Investigator who performed the program effort.

Test samples were developed and provided by Mr. Thomas K. De Lay, of the Materials and Processes Laboratory, Marshall Space Flight Center.

Tests were performed by Mr. Jeffery D. Craven of the Electromagnetic Environmental Effects Test Branch, Electro-Mechanical Test Division, Redstone Technical Test Center.

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1. INTRODUCTION

The ability of conductive metal of adequate thickness to withstand direct lightning strikes is well known. It can also protect underlying electronics against the indirect effects of lightning if joints and seams are electrically bonded to avoid gaps and holes in the enclosure.

It is also well known that nonconductive materials do not withstand direct strikes well and cannot provide shielding for underlying equipment.

It would appear that materials that were somewhat conductive such as graphite filled composites would lie somewhere between the two extremes. Simulated lightning tests were performed in order to help quantify the direct and indirect effects of lightning on composite materials. This report describes those tests and the results.

2. SUMMARY OF RESULTS

There was a considerable amount of damage to graphite fiber reinforced plastic (GFRP) surfaces and joints resulting from a simulated direct lightning strike. Generally the ability to withstand the strike depends upon the thickness of the GFRP. The addition of a top layer of expanded aluminum foil greatly reduces the depth of the damage from the "A" component of a simulated lightning strike. The addition of a second layer to the back side also reduces the damage from the "C" component. Aluminum honeycomb core material between two layers of GFRP did not do well because of separation of the layers by the "A" component.

Shielding effectiveness also depends upon the thickness of the GFRP and can be enhanced by adding one or two layers of expanded aluminum foil. All samples tested were capable of providing at least 30 dB of shielding of peak emissions from direct or remote lightning strikes.

3. DESCRIPTION OF TESTS

Individual samples of material were tested to determine shielding effectiveness, and pairs of the samples were used to determine damage to the surface and joints between samples. The samples included various thicknesses of graphite fiber reinforced plastic (GFRP), GFRP with metal enhancement, and conductive paint over fiberglass material. A typical sample configuration is shown in figure 1. All samples are described in table 1. Each test description refers to samples by their listed number.

Descriptions of the simulated lightning strike components "A", "C", and "D" used in these tests, the test equipment, and test procedures are found in the Redstone Technical Test Center (RTTC) report in appendix A.

The "D" component of a simulated lightning strike was used to determine shielding effectiveness of the samples. The test samples were 12 inch squares bolted over a 10 inch square opening in a large conductive enclosure containing sensors. The mating surfaces on most of the test samples were sanded to expose graphite and painted with conductive silver paint to enhance contact with the enclosure. Exceptions were samples 10A, a nonconductive fiberglass sample for comparison; 3A, a sample with expanded aluminum foil on the mating surface; and 9G, a GFRP unitape sample used for comparison to similar painted samples. The enclosure was made of aluminum instead of steel as stated in the test plan. The tests consisted of a remote strike to ground 3 meters away from the test sample and a strike directly to the test sample. Nonconductive bolts were used for both types of shielding tests. Test results are described beginning on page 7 of the RTTC report. In summary, the GFRP with double expanded foil layers provided the best shielding against emissions from the remote strike and the direct strike. The single foil layer did well especially against the remote strike. Generally the thicker samples of GFRP were better than the thinner samples, but the GFRP with aluminum honeycomb core did not do as well as some of the thicker GFRP samples. The GFRP unitape without silver paint on the mating surfaces provided the least amount of shielding.

Pairs of similar samples joined with lap or butt joints were tested to determine damage to the strike surface and to the joint between samples. The mating surfaces between most samples and from sample to ground were sanded and painted with conductive silver paint. The exceptions were samples 3A to 3B which had expanded aluminum foil on both sides and 9G to 9H which used plain GFRP for comparison. Samples 4C and 4D mated a painted surface to the expanded aluminum foil. Samples were subjected to the "A" component and the "C" component of a simulated lightning strike. The plastic bolts at the joints could not withstand the physical force produced by component "A", so metal bolts were used for the joint tests. Test descriptions and results are found in the RTTC report along with pictures of damaged samples. Further inspection of the actual samples resulted in more detailed descriptions of damage to the strike surface and the joints. Those descriptions are included here.

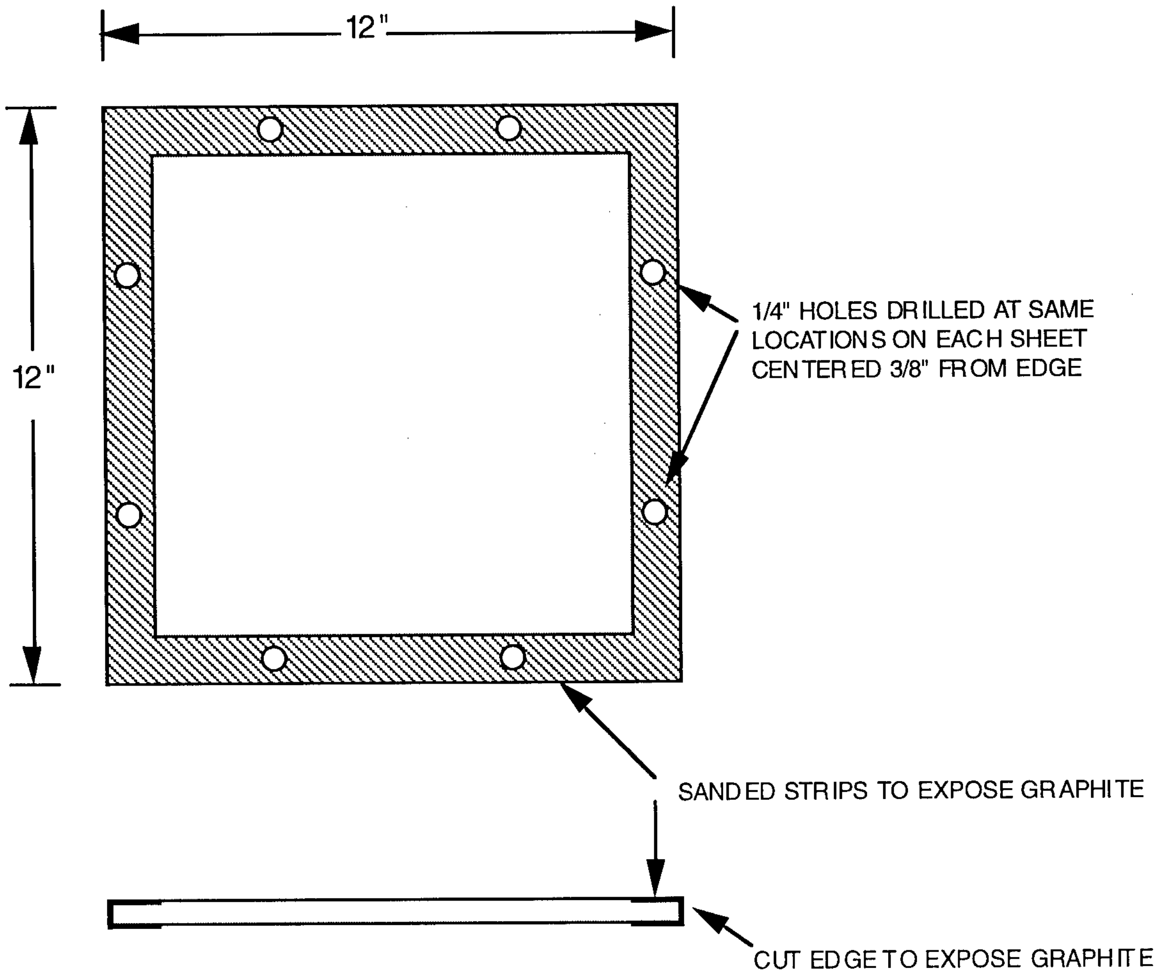

Figure 1. - Test Sample

Table 1. - Sample Description

SAMPLE TYPE	SAMPLE NO.	DESCRIPTION	MATING SURFACES PAINTED
Aluminum	x	Al. plate	
Honeycomb 0.730	1	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers one side, 8 on other; Aluminum core	4
Honeycomb 0.621	2a, b	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers each side; Aluminum core	4
Honeycomb 0.621	2c, d	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers each side; Aluminum core	2
Foil, two sides	3a, b	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers; Expanded Aluminum Foil	0
Foil, one side	4a, b	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers; Expanded Aluminum Foil	4
Foil, one side	4c, d, e, f, g	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers; Expanded Aluminum foil	2
GFRP 0.160	5	Amoco T-300 Fiber; Thiokol TCR Resin; 8 layers	4
GFRP 0.130	6	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers	4
GFRP 0.080	7a, b	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers	4
GFRP 0.068	8a, b	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers	4
GFRP 0.068	8c, d, e, f	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers	2
GFRP 0.068	8g, h	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers	2
GFRP Unitape	9a, b	Hercules AS4 Fiber; Hercules 3501 Resin; 6 double layers	4
GFRP Unitape	9c, d, e, f	Hercules AS4 Fiber; Hercules 3501 Resin; 6 double layers	2
GFRP Unitape	9g, h	Hercules AS4 Fiber; Hercules 3501 Resin; 6 double layers	0
Fiberglass 0.060	10a, b, c, d	Airtech Tool Rite; Owens Corning Fiber, Silver Paint Both Sides	0
Fiberglass 0.045	11a, b, c, d	Airtech Tool Rite; Owens Corning Fiber	ALL

4. RESULTS OF DIRECT STRIKE DAMAGE TESTS

Samples from these tests were inspected for four categories of damage. They are:

(1) Damage to the surface of the different materials from the "A" component and the "C" component.

(2) Comparison of damage to silver painted versus unpainted joint surfaces.

(3) Comparison of damage to lap joints versus butt joints with aluminum bridge across joint.

(4) Comparison of damage to butt joints with aluminum plate bridge versus aluminum foil bridge.

Results of tests 47 through 60 are described below. These are followed by results of each category assessment.

Component "C" followed component "A" in all tests. Note that expanded foil, when used as the top layer, was blown away by component "A", and component "C" was applied directly to the GFRP at the damaged spot.

Refer to the RTTC test report, in appendix A, for pictures of the front and back of each pair of samples used on each test.

Test 47 -- Honeycomb (0.621 inch), Lap Joint, Samples 2c-2d, Strike to 2c.

"A" component delaminated two layers.

Charred up to 3 inches across.

"C" component burned through 2 to 3 more layers.

Slight separation of front panel from honeycomb.

Painted lap joint slightly discolored.

No damage to joint surface.

Honeycomb expanded around bolt holes on 2c and 2d.

Test 48 -- Expanded Foil Both Sides (0.098 inch), Lap Joint, Samples 3a-3b, Strike to 3b.

"A" component burned 1.5 inch diameter of expanded foil.
"C" component burned 1 to 2 layers of GFRP.
Charred 1 inch around bolt holes.
Cracked some GFRP at joint.
Burned some foil on 3b-3a joint.
About same damage at joint to ground.

Test 49 -- Expanded Foil Top Side (0.073 inch), Lap Joint, Samples 4c-4d, Strike to 4c.

"A" component blew off 2/3 of expanded foil.
Charred 1 inch diameter GFRP.
"C" component burned through 3 to 4 layers of GFRP.
Total strike melted 1 inch on back side.
Some paint and melted epoxy from 4c stuck to foil on 4d at joint.
No damage to 4d mating surface.
Discolored at both joints.
Lifted some GFRP fibers on 4d at connection to ground.

Test 50 -- GFRP Mat (0.068 inch), Lap Joint, Samples 8c-8d, Strike to 8d.

"A" component burned 2.5 inch diameter through 2 layers GFRP.
"C" component burned 2 to 3 more layers.
Melted 1 inch on back side.
Burned 1 inch at bolt holes at joint.
Also burned 0.5 inch spots away from bolts in joint.
Painted edge discolored at lap and ground joints.

Test 51 -- GFRP Unitape (0.062 inch), Lap Joint, Samples 9c-9d, Strike to 9c.

"A" component blew out 4 layers of GFRP, 5 inch diameter.

Frayed from center to joint, 4 inch wide strip.
Split back side.
"C" component burned through 2 to 3 more layers.
Charred back side.
Burned front of joint and split back side near bolt holes.
Cracked across 9d two inches from lap and ground joints.
Discolored paint and melted some epoxy into both joints.

Test 52 -- GFRP Unitape (0.062 inch), Lap Joint, No Paint, Samples 9g-9h, Strike to 9h.

"A" component frayed 4 inch diameter, 3 to 4 layers.
Fiber split on front and cracked on back side.
"C" component burned through 3 to 4 more layers.
Melted 1 inch on back side.
Joint on 9h burned, but better than 9e-9f or 9c-9d.
Frayed 9g just above joint.
Some splitting at holes at lap and ground joints.
Some melting at lap and ground joints.

Test 53 -- Fiberglass, Both Sides Silver Painted, Samples 11b-11c, Strike to 11b.

"A" Component blew off most silver paint.
Joint still intact but strips of silver blown off.
"C" component would not conduct through remaining silver.

Test 54 -- Honeycomb (0.621 inch), Butt Joint, Samples 2a-2b, Strike to 2a.

"A" component only, no "C" component.
Strike to 2a delaminated 2 to 3 layers, 3.5 inches across.
Cracked through 2 layers.
Expanded honeycomb, and blew off back panel of GFRP.
Separated front panel from honeycomb but stayed together.
Very little effect on butt joint or to ground joint on 2b.
Some discolored silver on painted edge.
No damage to surface of joint.

Test 55 -- Expanded Foil Both Sides (0.098 inch), Butt Joint, Samples 3a-3b, Strike to 3a.

"A" component burned 1 inch diameter of aluminum foil.

"C" component burned through 2 to 3 layers of GFRP.

Damage at butt joint less than for lap joint.

Expanded foil burned through at several points on 3a and 3b edges.

Small discoloration at 3b to ground connection.

Some expanded foil burned at ground connection.

Test 56 -- Expanded Foil Top Side (0.073 inch), Butt Joint, Samples 4e-4f, Strike to 4f.

"A" component blew off and disintegrated 5 inch diameter foil.

Charred 1 inch diameter GFRP.

"C" component burned through 3 or 4 layers of GFRP.

Melted 0.5 inch on back side.

Took off scattered foil on 4e and 4f at joint.

Foil stuck to aluminum bridge in some places.

Discolored silver painted joint to ground.

Test 57 -- GFRP Mat (0.068 inch), Butt Joint, Samples 8e-8f, Strike to 8e.

"A" component burned 4 inch diameter in GFRP.

Charred and delaminated but not frayed.

"C" component burned through 4 to 5 layers.

No damage on back side.

Joint discolored on painted edges.

Some carbon stuck to bridge in small spot.

Some damage to GFRP just above silver paint on 8e and 8f.

Similar damage at 8f to ground joint.

Test 58 -- GFRP Mat (0.068 inch), Butt Joint, Aluminum Foil Bridge, Samples 8g-8h, Strike to 8g.

"A" component charred 3.5 inch diameter GFRP.

Fibers raised 2 inch diameter.

No "C" component.

No damage to back side.

Joint not bad but foil blown completely away.

Slightly raised fibers just above joint on 8g and 8h.

Some of same on 8h to ground joint.

Test 59 -- GFRP Unitape (0.062 inch), Butt Joint, Samples 9e-9f, Strike to 9f.

"A" component blew out 4 layers, 4 inch diameter.

Split fibers from center to joint.

Not as frayed as 9c-9d lap joint.

"C" component burned 2 to 3 more layers.

Melted 1.25 inch on back side.

Fibers split out just above joint plate on 9e and 9f.

Discolored paint at joint.

Some fibers split at holes in 9e.

Both butt and ground joints had epoxy melted to bridge.

Test 60 -- Fiberglass, Both Sides Silver Painted, Butt Joint, Samples 11a-11d, Strike to 11d.

"A" Component blew off most silver paint on strike surface.

Joint still intact, but strips of silver blown off.

"C" component would not conduct through remaining silver.

5. CONCLUSIONS -- DIRECT STRIKE DAMAGE TESTS

Results of assessment of each of the four categories along with the test and sample numbers used for comparison that led to the conclusions are given below. Where differences in damage are clear cut, the sample configurations are listed in order of acceptability.

Damage from Direct Strike:

1. Expanded metal on both sides (0.098 inch)
Test 48, Sample 3b; Test 55, Sample 3a.
"A" Component Damage: Burned 1.5 inch diameter on foil, and 1 inch diameter spot on GFRP.
"C" Component Damage: Burned through 1 to 3 layers of GFRP.

2. Expanded metal on top side (0.073 inch)
Test 49, Sample 4c; Test 56, Sample 4f.
"A" Component Damage: Blew off 2/3 of foil, charred 1 inch diameter spot on GFRP, melted 0.5 inch spot on back.
"C" Component Damage: Burned through 3 to 4 layers of GFRP, 1 inch diameter spot melted on back.

3. GFRP mat (0.068 inch)
Test 50, Sample 8d; Test 57, Sample 8e; Test 58, Sample 8g.
"A" Component Damage: Burned 2.5 inch to 4 inch diameter spot through two layers of GFRP.
"C" Component Damage: Burned through 2 to 4 layers of GFRP.

4. GFRP Unitape (0.062 inch)
Test 51, Sample 9c; Test 52, Sample 9h; Test 59, Sample 9f.
"A" Component Damage: Blew out 4 to 5 single layers of GFRP, frayed 4 inch to 5 inch diameter spot, split and cracked both sides of sample.

"C" Component Damage: Burned through 2 to 4 layers of GFRP, melted up to 1.25 inch diameter spot on back.

5. Honeycomb (0.621 inch)
Test 47, Sample 2c; Test 54, Sample 2a.
"A" Component Damage: Delaminated and blew off GFRP panel from back side, expanded aluminum core.
"C" Component Damage: Burned 2 to 3 layers of GFRP on top panel.

6. Silver Paint on both sides of Fiberglass (0.060 inch)
Test 53, Sample 11b; Test 60, Sample 11d.
"A" Component damage: Burned off large portion of silver paint at strike point and along streaks to the joint.
"C" Component damage: Not enough conductive surface left after "A" strike to conduct "C" current.

Silver Painted vs. Unpainted Joints:

1. Silver painted butt joint
Test 59, Sample 9e-9f.
Some damage above joint.
Split at bolt holes.
Melted epoxy onto bridge.

2. Silver painted lap joint
Test 51, Sample 9c-9d.
Burned front.
Split above joint.
Split near bolt holes.
Melted epoxy into joint.

3. Unpainted lap joint
Test 52, Sample 9g-9h.
Frayed fibers all along edge of joint.
Charred one layer deep.
Some splitting at holes and above joint.

Lap Joints vs. Butt Joints:

Lap Joints -- Test 47, Sample 2c-2d; Test 48, Sample 3a-3b; Test 49, Sample 4c-4d; Test 50, Sample 8c-8d; Test 51, Sample 9c-9d.
Butt Joints -- Test 54, Sample 2a-2b; Test 55, Sample 3a-3b; Test 56, Sample 4e-4f; Test 57, Sample 8e-8f; Test 59, Sample 9e-9f.
No discernible differences between lap joint and butt joint with 0.125 inch aluminum plate bridge.
"C" component does most damage at joint.
"A" component knocked off foil bridge.

Foil vs. Aluminum Plate Bridge:

Aluminum plate bridge -- Test 57, Sample 8e-8f.
Foil bridge -- Test 58, Sample 8g-8h.
Foil bridge blown off by "A" component, no "C" component test.
Surface damage to joint was less than for plate that had "A" and "C" components.

Loss of foil bridge makes it unacceptable for connections that may carry lightning current. Bridge should be thick enough and be well attached to prevent damage from "A" component.

APPENDIX

RTTC Test Report

TEST REPORT OF THE DIRECT STRIKE AND NEAR STRIKE LIGHTNING TESTS OF THE COMPOSITE MATERIAL SAMPLES

Jeffery D. Craven
Electromagnetic Environmental Effects Test Branch
Electro-Mechanical Test Division
Redstone Technical Test Center

January 1997

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REFERENCE OR OFFICE SYMBOL	SUBJECT
	Initial, OPSEC, and Patent Applicability Reviews

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PART I - INITIAL REVIEW
(Use Only for Unclassified Reports & Publications)

The attached information, Test Report of the Direct Strike and Near Strike Lightning Tests of Composite Material Tiles has been reviewed in RTTC by Jeffery D. Craven and determined to be factual and unclassified.

Jeffery D. Craven

26 March 97
DATE

PART II - OPSEC REVIEW
(Use Only for Unclassified Reports & Publications)

The attached information, Test Report of Direct Strike & Near Strike Lightning Tests of Composite Material Tiles has been given an OPSEC reviewed in ____________ by ____________ and determined to be unclassified, nonsensitive, and suitable for public release.

____

____
DATE

PART III - PATENT APPLICABILITY REVIEW
(Use Only for Classified & Unclassified Reports & Publications)

The attached information, Test Report of Direct Strike & Near Strike Lightning Tests of Composite Tiles has been reviewed for patent applicability, in RTTC by Jeffery D. Craven. The information

(X) appears to contain no patentable material.
( ) appears to contain patentable material.

( ) patent disclosure has been submitted.
( ) patent disclosure should be submitted.

Jeffery D. Craven

26 March 97
DATE

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EXECUTIVE SUMMARY

This report presents the test procedures and results of the near strike and direct strike lightning effects test on the composite material tiles.

The objectives of this test effort were to determine the direct effects of the cloud-to-ground lightning environment on the composite material tiles and to determine the attenuation characteristics of the composite material with respect to the DS and NS lightning environments.

There were no criteria for this test effort since it was an investigative study to determine the effects of the lightning environment on the composite material samples.

With respect to shielding effectiveness, samples 3A and 3B demonstrated the highest shielding effectiveness. The lowest shielding effectiveness levels were demonstrated by samples 9B, 9G, and 11A.

All of the panels experienced some degree of damage due to the direct strike lightning environment consisting of the initial stroke (Component A) and the continuing current (Component C). The least amount of visual damage to the lap joint was observed on samples 2C-2D despite significant damage at the point of discharge. Samples 9C-9D and 9G-9H experienced significant lap joint damage as well as significant damage at the point of discharge. Samples 11B-11C experienced sufficient damage to preclude testing of the continuing current (low voltage) waveform.

The least amount of visual damage to the butt joint was observed on samples 3A-3B and 8E-8F. The continuing current waveform could not be conducted on samples 2A-2B due to excessive damage to sample 2A from the initial stroke; the outer layer of sample 2A was separated from the aluminum honeycomb core. Additionally, the initial stroke current waveform was not recorded on test #54 due to disconnection of the ground cable (measurement point) as a result of the sample 2A separation of the outer layer from the aluminum honeycomb core. The continuing current waveform could not be conducted on samples 8G-8H due excessive damage to the foil bridge, which electrically connected samples 8G and 8H, from the initial stroke. Samples 11C-11D experienced sufficient damage to preclude testing of the continuing current (low voltage) waveform.

I. INTRODUCTION

This report presents the test procedures and results of the direct strike (DS) and near strike (NS) lightning tests conducted on the composite material samples. The tests were conducted during November and December 1996 at the Simulated Lightning Effects Test (SLET) Facility and Transportable Lightning Effects Simulator (TLES) Facility located at Building 8975 on Redstone Arsenal. The tests were conducted by personnel of the Electromagnetic Environmental Effects (E3) Test Branch, Electro-Mechanical Test Division, Redstone Technical Test Center (RTTC).

II. TEST OBJECTIVE

The objectives of these tests were to determine the direct effects of the cloud-to-ground lightning environment on the composite material samples and to determine the attenuation characteristics of the composite material with respect to the DS and NS lightning environments. The direct effects to the composite material and to the joints between composite material samples were evaluated by inspection of the simulated DS lightning contact point and the mating surfaces of the joints between the composite material samples. The indirect effects were evaluated by measuring the attenuation of the magnetic field rate-of-change and the peak electric field from both the DS and NS lightning environments.

III. TEST ENVIRONMENT

The simulated direct strike lightning environment utilized for the conduct of these tests were taken form NSTS-07636. Since these tests were a general test of composite materials that may be installed anywhere on a space vehicle, then the most severe lightning environment was utilized.

1. Direct Effects. The direct effects of lightning are the burning, eroding, blasting, and structural deformation caused by lightning arc attachment, as well as the high pressure shock waves and magnetic forces produced by the associated high currents. For qualification testing, current components A through D are utilized to determine direct effects. Components A, B, C and D each simulate a different characteristic of the current in a natural lightning flash and are shown in Figure 1. The direct effects from the average amplitude of the intermediate current is negligible with respect to the direct effects from the peak amplitude of the initial stroke and the direct effects from the maximum charge transfer of the intermediate current is negligible with respect to the direct effects from the charge transfer of the continuing current; therefore, the intermediate current waveform was not utilized for this test effort, but is described herein for completeness only.

a. Initial Stroke. The initial stroke (Component A) has a peak amplitude of 200 kiloamperes (kA) (±10 percent) and an action integral of 2×10^6 amperes squared seconds ($A^2 \bullet sec$) (±20 percent) with a total time duration not exceeding 500 microseconds (µsec). This component may be unidirectional, e.g., rectangular, exponential or linearly decaying, or oscillatory.

b. Intermediate Current. The intermediate current (Component B) has an average amplitude of 2 kA (±10 percent) flowing for a maximum duration of 5 milliseconds (msec) and a maximum charge transfer of 10 Coulombs (C). The waveform shall be unidirectional.

c. Continuing Current. The continuing current (Component C) transfers a charge of 200 C (±20 percent) in a time of between 0.25 and 1 second. The waveform shall be unidirectional.

d. Restrike Current. The restrike current (Component D) has a peak amplitude of 100 kA (±10 percent) and an action integral of 0.25×10^6 $A^2 \bullet sec$ (±20 percent). This component may be either unidirectional or oscillatory with a total time duration not exceeding 500 μsec.

2. Indirect Effects. The indirect effects of lightning are predominantly those resulting from the interaction of the electromagnetic fields accompanying lightning with electrical apparatus in the system. Indirect effects are produced by both direct strike and near strike lightning events. For these tests current Component D was utilized to determine indirect effects. The near strike lightning environment for these tests was established as the electromagnetic fields associated with a 3 meter separation distance from the Component D discharge.

IV. EVALUATION CRITERIA

There were no pass/fail evaluation criteria for this test effort. Instead, these tests were investigative processes to determine the direct effects of lightning to the various composite materials and to determine the shielding effectiveness of the various composite materials to the lightning environment.

V. TEST RESPONSIBILITY

1. Redstone Technical Test Center. The RTTC was responsible for planning and conducting all tests, coordinating and scheduling test facilities, establishing and applying security and safety procedures, providing instrumentation and test fixtures, modifying test hardware as required, collecting and analyzing test data, and providing a final report.

2. Tec-Masters, Incorporated (Inc.). Tec-Masters, Inc., was responsible for providing overall coordination of the test program, including, but not limited to, supplying technical assistance, identifying and providing all test hardware, and support hardware, providing a test plan, and for the damage evaluation of composite materials.

3. George C. Marshall Space Flight Center. George C. Marshall Space Flight Center (MSFC), National Aeronautics and Space Administration (NASA), was responsible for providing the funds for this program through Tec-Masters, Inc.

VI. FACILITIES AND EQUIPMENT REQUIREMENTS

This section describes the test hardware, facility and instrumentation utilized to conduct the direct effects and indirect effects lightning tests of the composite material samples.

1. Test Hardware. The test hardware was provided by Tec-Masters, Inc., and consisted of twenty-six, 12-inch by 12-inch samples. Seven samples were graphite filament mat, five samples were graphite filament unitape, five samples were honeycomb aluminum with graphite mats on top and bottom, three samples were nonconductive epoxy with no conductive filler nor sanded edges, three samples were GFRP mat with wire mesh screen on top, two samples were GFRP mat with wire mesh screen on top and bottom, and one sample was fiberglass for calibration purposes. Appendix D is a tabulated description of the composite material samples. RTTC provided one aluminum plate sample for calibration purposes, also.

2. TLES Facility. This section describes the various components comprising TLES Facility.

a. Initial Stroke (Component A) Capacitor Bank. The TLES initial stroke current capacitor bank consists of 40 capacitors, each rated at 30 kV and 111 μF, configured as a two-stage Marx bank with a total calculated capacitance of 69.375 μF and an output voltage of 240 kV. A 2.25 μF, 252 kV peaking capacitor circuit is utilized in conjunction with the initial stroke capacitor bank to increase the current rate-of-rise time to 6.5 μsec. The initial stroke capacitor bank can generate a 200 kA ± 10% peak current simulated Component A direct strike lightning waveform with an action integral of 2.0×10^6 A^2sec ± 20%. A Hipotronics Model No. 8150-100 High Voltage DC Power Supply, rated for 150 kV and 100 mA, is utilized to charge the TLES initial stroke capacitor bank.

b. Continuing Current (Component C) Capacitor Bank. The TLES continuing current capacitor bank consists of two layers of electrolytic capacitors connected in series. Each layer contains 196 capacitors, each rated at a minimum 450 V and 3000 μF, in parallel. The total measured capacitance is 0.37 F and is charged to a nominal value of 750 V. The continuing current capacitor bank can generate a simulated Component C waveform with 200 C ± 20% of charge transfer. A Hipotronics Model No. 801-5A High Voltage DC Power Supply, rated for 1 kV and 5 A, is utilized to charge the TLES continuing current capacitor bank.

3. SLET Facility. The SLET facility is comprised of a restrike (Component D) Marx capacitor bank for conducting near strike lightning testing and direct strike lightning testing (only to Component D) of inert systems. The SLET capacitor bank consists of a 36-stage Marx bank enclosed within a non-conductive fiberglass structure with a total calculated capacitance of 20.8 nanofarads (nF). Each stage, consisting of a 150 kV, 0.75 μf capacitor, is normally charged to 75 kV to provide a total output voltage of 2.7 MV. Energy from the Marx bank is delivered to the peaking capacitor grid/spark gap assembly via bus wires. The peaking capacitor grid consists of two parallel, 150-foot long by 132-foot wide wire grids with a 30-foot high separation. The calculated capacitance for the SLET peaking capacitor grid is 1.78 nF. The SLET restrike Marx capacitor bank can generate a 70 kA ± 10% peak current simulated Component D waveform with an average current rate-of-rise of 1.0×10^{11} A/sec and a maximum current rate-of-rise of 1.4×10^{11} A/sec ± 20%. A Hipotronics Model No. 8100-250 High Voltage DC Power Supply, rated for 100 kV and 250 mA, is utilized to charge the SLET restrike current capacitor bank.

4. Test Instrumentation. The objective of the test effort was to subject the composite material samples to a simulated direct strike lightning test and a simulated near strike lightning test to determine the direct and indirect effects. Instrumentation was necessary to monitor the injection current waveforms (stimulus) to insure compliance with the simulated direct strike lightning environment criteria. Instrumentation was also necessary to monitor the magnetic field rate of change and the peak electric field in order to determine shielding effectiveness of the composite material samples.

a. Initial Stroke Current Instumentation. A Pearson Model 1080 Current Probe was utilized as the sensor for the high current waveform measurement. The current probe was installed on the ground return of the initial stroke discharge probe. The high current waveform measurement was telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal was recorded on a Hewlett-Packard Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

b. Continuing Current Instrumentation. A 0.12 Ohm series resistor was utilized as the sensor for the continuing current waveform measurement. The resistor was installed in-line with the continuing current transmission line. The continuing current waveform measurement was telemetered via a Meret Model MDL281-4-C Fiber Optic System. The signal was recorded on an HP 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

c. Restrike Current Instrumentation. A Pearson Model 1080 Current Probe was utilized as the sensor for the high voltage restrike waveform measurement. The current probe was installed on the center conductor of the restrike current down conductor. The high voltage restrike waveform measurement was telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal was recorded on an HP Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

d. Peak Electric Field Sensor. The peak electric field waveform was measured with a Nanofast Model EFS-1 peak electric field sensor (Figure 2). The peak electric field sensor was placed in the center of the conductive (aluminum) enclosure to monitor the peak electric field for shielding attenuation comparisons between the composite material samples. The peak electric field measurement was telemetered via a Nanofast OP-300 Fiber Optic Systems to a shielded area for processing. The signal was recorded on an HP Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

e. Magnetic Field Rate of Change (B-dot) Sensor. The magnetic field rate of change waveform was measured with an EG&G Model MGL-2 B-Dot sensor (Figure 3). The B-dot sensor was placed in the center of the conductive (aluminum) enclosure to monitor the peak electric field for shielding attenuation comparisons between the composite material samples. The magnetic field rate of change measurement was telemetered via a Nanofast OP-300 Fiber Optic Systems to a shielded area for processing. The signal was recorded on an HP Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

f. Conductive (Aluminum) Enclosure. A 4-foot wide by 4-foot high by 4-foot long aluminum enclosure (Figure 4) was fabricated by RTTC to facilitate shielding measurements of the various composite material samples. All sides were welded at the seams except for one side which was mounted with machine screws. This was necessary to allow access into the conductive enclosure to setup the B-dot sensor and the peak electric field sensor. The spacing between the screws was 6 inches. Also, one side (not the unwelded side) had a 10-inch wide by 10-inch long square opening configured to allow the various composite material samples to be mounted to the conductive enclosure. Nylon and fiberglass bolts and nuts were utilized to secure the composite material samples. Use of nonconductive bolts and nuts allowed the induced skin currents to flow from the composite material sample to the conductive enclosure across the mating surface between the composite material sample and the conductive enclosure rather than through the bolts.

VII. TEST PROCEDURE

The composite material samples were subjected to the simulated direct strike lightning environment to determine the structural effects of direct strike lightning. Indirect effects testing of the composite material samples was conducted with both the simulated direct strike lightning environment and the simulated near strike lightning environment to establish attenuation comparisons between the composite material samples. The lightning tests were divided into three phases: near strike shielding measurement test; direct strike shielding measurement test; and direct strike joint damage test (direct strike test with the composiste material samples in a lapped configuration and direct strike test with the composite material samples in a butted joint with aluminum plate bridge configuration`

1. <u>Near Strike Shielding Measurement Test</u>. The following test procedure was followed for the near strike lightning test sequence:

a. Setup conductive enclosure 3 meters from the simulated lightning discharge point.

b. Perform pre-test calibration of the SLET lightning generator.

c. Setup peak electric field sensor in the conductive enclosure (Figure 2).

d. Install aluminum plate sample on the conductive enclosure.

e. Secure test area and setup measurement system.

f. Charge SLET lightning generator to specified test level.

g. Discharge SLET lightning generator.

h. Record test data.

i. Repeat steps d. through h. for the fiberglass sample.

j. Repeat steps d. through h. for all the designated composite material samples.

k. Repeat steps c. through j. for B-dot sensor (Figure 3).

2. Direct Strike Shielding Measurement Test. The following test procedure was followed for the direct strike lightning test sequence:

a. Position the conductive enclosure 1 meter below the simulated lightning discharge probe as shown in Figure 4.

b. Perform pre-test calibration of the SLET lightning generator.

c. Setup B-dot sensor in the conductive enclosure.

d. Install aluminum plate sample on the conductive enclosure and position leader wire as shown in Figure 5.

e. Secure test area and setup measurement system.

f. Charge SLET lightning generator to specified test level.

g. Discharge SLET lightning generator (Figure 6).

h. Record test data.

i. Repeat steps d. through h. for the fiberglass sample.

j. Repeat steps d. through h. for all the designated composite material samples.

k. Repeat steps c. through j. for peak electric field sensor.

3. Direct Strike Joint Damage Test. The following test procedure was followed for the direct strike joint damage lightning test sequence:

a. Perform pre-test calibration of the TLES lightning generator.

b. Setup designated composite material samples in lapped configuration (Figure 7).

c. Secure test area and setup measurement system.

d. Charge TLES lightning generator to specified test level.

e. Discharge TLES lightning generator (Figure 8).

f. Inspect sample damage and record test data.

g. Repeat steps b. through f. for all the designated composite material samples.

h. Repeat steps b. through g. for designated composite material samples configured in a butted joint configuration.

4. Deviations to the Test Plan. Two deviations from the test procedures (Appendix A) were performed during the lightning test of the composite material samples. The first deviation was to conduct magnetic field rate-of-change measurements rather than peak electric field measurements on test numbers 27 through 39; and subsequently, conduct peak electric field measurements rather than magnetic field rate-of-change measurements on test numbers 40 through 46. The second deviation consisted of not conducting the Component C (continuing current) attachment to test numbers 53, 54, 58 and 60.

a. The first deviation allowed higher fidelity of the shielding measurements. The sensitivity of the B-dot sensor was lower than the sensitivity of the peak electric field sensor, thus allowing a greater range of measurements above the sensor noise level. Therefore, the type of measurements for test numbers 27 through 46 were reversed (peak electric field and magnetic field rate-of-change) since a majority of the composite material sample types were originally planned to conduct direct strike peak electric field shielding measurements (eleven types for peak electric field shielding measurements versus only six types for magnetic field rate-of-change shielding measurements).

b. The second deviation from the test procedure was due to excessive damage by the Component A (initial stroke) attachment to the composite material samples utilized on test numbers 53, 54, 58 and 60. As a result of this damage, the Component C (continuing current) current waveform would not discharge to the composite material samples. The Component C lightning generator operates at a low voltage (approximately 750 to 800 volts); therefore, a good ground return path throughout the entire discharge network must be maintained. Since the Component A attachment caused excessive damage to these samples, thereby resulting in an open circuit at the composite material sample interface, then the Component C current waveform would not discharge to the composite material samples.

VIII. RESULTS

1. Near Strike Shielding Measurement Test. The composite material samples experienced no damage as a result of the near strike shielding measurement test. The near strike peak electric field shielding measurement tests are represented by tests #1 through #13. The near strike magnetic field rate-of-change shielding measurement tests are represented by tests #14 through #26. Appendix E summarizes the calculation process for determining the shielding effectiveness correlation between the composite material samples.

a. The baseline for determining the maximum peak electric field shielding value was established by measuring the peak electric field within the conductive enclosure with the aluminum panel installed. The peak electric field measured within the conductive enclosure with the aluminum panel installed was below the noise level of the measurement equipment. Therefore, the noise level of 35.8 volts per meter (V/m) was established as the maximum peak electric field shielding baseline value. Similarly, the minimum peak electric field shielding value was established by measuring the peak electric field within the conductive enclosure with the fiberglass panel installed. The peak electric field measured within the conductive enclosure with the fiberglass panel installed was 1200 V/m; resulting in a measureable range of 30.5 decibels (dB) for the peak electric field shielding measurement. All the peak electric field measurements for the composite material samples were below the noise level of the measuring equipment, except for sample 9G (GFRP Unitape, 0.062, no paint) on test #12. A peak electric field of 48.8 V/m was measured for sample 9G. Table 1 is a tabulation of the peak electric field measurments for the composite material samples with respect to the near strike lightning environment.

Test No.	Sample	Current Probe Factor	Gain (dB)	Peak Current (kA)	Peak E-Field Probe Output (mV)	Peak E-Field Probe Factor	Peak E-Field (V/m)	Correlation to Fiberglass (dB)
1	Aluminum	400 A/V	-48	62	17.9	1 V = 2 kV/m	35.8	30.5
2	Fiberglass	400 A/V	-48	62	600.0	1 V = 2 kV/m	1200.0	0.0
3	1	400 A/V	-48	62	17.1	1 V = 2 kV/m	34.2	30.9
4	2A	400 A/V	-48	63	19.5	1 V = 2 kV/m	39.0	29.9
5	3A	400 A/V	-48	63	16.3	1 V = 2 kV/m	32.6	31.5
6	4A	400 A/V	-48	63	13.0	1 V = 2 kV/m	26.0	33.4
7	5	400 A/V	-48	62	15.4	1 V = 2 kV/m	30.8	31.8
8	6	400 A/V	-48	63	18.7	1 V = 2 kV/m	37.4	30.3
9	7A	400 A/V	-48	68	17.9	1 V = 2 kV/m	35.8	31.3
10	8A	400 A/V	-48	68	19.5	1 V = 2 kV/m	39.0	31.6
11	9A	400 A/V	-48	68	17.9	1 V = 2 kV/m	35.8	31.3
12	9G	400 A/V	-48	69	24.4	1 V = 2 kV/m	48.8	28.7
13	11A	400 A/V	-48	68	17.9	1 V = 2 kV/m	35.8	31.3

Table 1. Near Strike Lightning Peak E-field Measurements.

Table 2 is a tabulation of comparisons of the shielding effectiveness in decibels between the various composite material samples with respect to the peak electric field measurement due to the near strike lightning environment. Variances with respect to the stimulus were taken into account to adjust the correlation between the various samples. A negative value in Table 2 indicates that the sample on the row is lower (worse) in shielding by the indicated amount in decibels than the sample on the column; conversely, a positive value indicates that the sample on the row is higher (better) in shielding by the indicated amount in decibels than the sample on the column. Sample 9G exhibited the least shielding effectiveness while sample 4A (GFRP with wire mesh on top side, 0.073) exhibited the most shielding effectiveness with respect to the peak electric field due to the near strike lightning environment. It should be noted that all of the sample measurements were below the noise level of the measurement equipment except for sample 9G; therefore, virtually no difference exists between the samples as tested with respect to the peak electric field due to the near strike lightning environment. Even the shielding effectiveness of sample 9G was only 4.7 dB below that of sample 4A.

Sample	1	2A	3A	4A	5	6	7A	8A	9A	9G	11A
1	-	1.0	-0.6	-2.5	-0.9	0.6	-0.4	0.3	-0.4	2.2	-0.4
2A	-1.0	-	-1.6	-3.5	-1.9	-0.4	-1.4	-0.7	-1.4	1.2	-1.4
3A	0.6	1.6	-	-2.0	-0.4	1.2	0.1	0.9	0.1	2.7	0.1
4A	2.5	3.5	2.0	-	1.6	3.2	2.1	2.9	2.1	4.7	2.1
5	0.9	1.9	0.4	-1.6	-	1.8	0.5	1.2	0.5	3.1	0.5
6	-0.6	0.4	-1.2	-3.2	-1.8	-	-1.0	-0.3	-1.0	1.5	-1.0
7A	0.4	1.4	-0.1	-2.1	-0.5	1.0	-	0.7	0.0	2.6	0.0
8A	-0.3	0.7	-0.9	-2.9	-1.2	0.3	-0.7	-	-0.7	1.8	-0.7
9A	0.4	1.4	-0.1	-2.1	-0.5	1.0	0.0	0.7	-	2.6	0.0
9G	-2.2	-1.2	-2.7	-4.7	-3.1	-1.5	-2.6	-1.8	-2.6	-	-2.6
11A	0.4	1.4	-0.1	-2.1	-0.5	1.0	0.0	0.7	0.0	2.6	-

Table 2. Near Strike Lightning Peak E-field Shielding Effectiveness Comparisons.

b. The baseline for determining the maximum and minimum magnetic field rate-of-change shielding values were established by utilization of the same procedure used for the measurment of the peak electric fields. The maximum magnetic field rate-of-change shielding baseline value was established with the aluminum panel installed on the conductive enclosure. The output signal of the B-dot sensor with the aluminum panel installed was 7.35 millivolts (mV). The minimum magnetic field rate-of-change shielding baseline value was established with the fiberglass panel installed on the conductive enclosure. The output signal of the B-dot sensor with the fiberglass panel installed was 9.51 volts (V); resulting in a measureable range of 62.2 dB for the magnetic field rate-of-change shielding measurement. Table 3 is a tabulation of the output signal of the B-dot sensor for the magnetic field rate-of-change measurements for the composite material samples with respect to the near strike lightning

Test No.	Sample	Current Probe Factor	Gain (dB)	Peak Current (kA)	Scope Reading (mV)	Receiver Gain (dB)	B-dot Measurement (mV)	Correlation to Fiberglass (dB)
14	Aluminum	400 A/V	-48	69	29.25	12	7.35	62.2
15	Fiberglass	400 A/V	-48	69	600.00	-24	9509.36	0.0
16	1	400 A/V	-48	70	290.00	12	72.84	42.4
17	2A	400 A/V	-48	69	290.00	12	72.84	42.3
18	3A	400 A/V	-48	69	51.00	12	12.81	57.4
19	4A	400 A/V	-48	69	200.00	12	50.24	45.5
20	5	400 A/V	-48	68	220.00	12	55.26	44.6
21	6	400 A/V	-48	69	234.00	12	58.78	44.2
22	7A	400 A/V	-48	69	272.00	12	68.32	42.9
23	8A	400 A/V	-48	69	350.00	12	87.92	40.7
24	9A	400 A/V	-48	69	413.00	12	103.74	39.2
25	9G	400 A/V	-48	69	478.00	6	239.57	32.0
26	11A	400 A/V	-48	68	160.00	6	80.19	41.4

Table 3. Near Strike Lightning Magnetic Field Rate-of-Change Measurements.

environment. Table 4 is a tabulation of comparisons of the shielding effectiveness between the various composite material samples with respect to the magnetic field rate-of-change measurement due to the near strike lightning environment. Variances with respect to the stimulus were taken into account to adjust the correlation between the various samples. The sample with the maximum shielding effectiveness with respect to the magnetic field rate-of-change was sample 3A (GFRP, wire mesh on both sides, 0.098, no paint); an output signal of 12.81 mV was measured. The sample with the minimum shielding effectiveness with respect to the magnetic field rate-of-change was sample 9G (GFRP Unitape, 0.62, no paint); an output signal of 239.57 mV was measured. Therefore, a measureable range of 25.4 dB was exhibited between the maximum and minimum magnetic field rate-of-change sheilding values for the composite material samples with respect to the near strike lightning environment.

Sample	1	2A	3A	4A	5	6	7A	8A	9A	9G	11A
1	-	0.1	-15.0	-3.1	-2.1	-1.7	-0.4	1.8	3.2	10.5	1.1
2A	-0.1	-	-15.1	-3.2	-2.3	-1.9	-0.6	1.6	3.1	10.3	1.0
3A	15.0	15.1	-	11.9	12.8	13.2	14.5	16.7	18.2	25.4	16.1
4A	3.1	3.2	-11.9	-	1.0	1.4	2.7	4.9	6.3	13.6	4.2
5	2.1	2.3	-12.8	-1.0	-	0.4	1.7	3.9	5.3	12.6	3.2
6	1.7	1.9	-13.2	-1.4	-0.4	-	1.3	3.5	4.9	12.2	2.8
7A	0.4	0.6	-14.5	-2.7	-1.7	-1.3	-	2.2	3.6	10.9	1.5
8A	-1.8	-1.6	-16.7	-4.9	-3.9	-3.5	-2.2	-	1.4	8.7	-0.7
9A	-3.2	-3.1	-18.2	-6.3	-5.3	-4.9	-3.6	-1.4	-	7.3	-2.1
9G	-10.5	-10.3	-25.4	-13.6	-12.6	-12.2	-10.9	-8.7	-7.3	-	-9.4
11A	-1.1	-1.0	-16.1	-4.2	-3.2	-2.8	-1.5	0.7	2.1	9.4	-

Table 4. Near Strike Lightning Magnetic Field Rate-of-Change Shielding Effectiveness Comparisons.

2. Direct Strike Shielding Measurement Test. The composite material samples experienced minimal damage with respect to the restrike current (Component D) direct strike shielding measurement tests. Typically, the damage was limited to a small area of burning and fraying of the material at the point of attachment. A small leader wire was positioned in the center of the sample to direct the direct strike to the sample surface instead of the edge of the opening of the conductive enclosure (Figure 5). The direct strike peak electric field shielding measurement tests are represented by tests #40 through #46. Originally, the magnetic field rate-of-change shielding measurement tests were to be tests #40 through #46, but since the sensitivity of the B-dot sensor was lower than the peak electric field sensor, the test plan was modified to allow the maximum amount of samples to be tested with the B-dot sensor (see explanation for test plan deviations in paragraph VII.4.a. above). Subsequently, the direct strike magnetic field rate-of-change shielding measurement tests are represented by tests #27 through #39.

a. The baseline for determining the maximum and minimum peak electric field shielding values were the same as utilized during the near strike shielding measurement test. The maximum peak electric field shielding baseline value was established with the aluminum panel installed. The measurement was below the noise level of the measuring equipment; therefore, the noise level of 34.2 V/m was established as the maximum peak electric field shielding baseline value. The minimum peak electric field shielding value was established with the fiberglass panel installed. A measurement of 12 kilovolts per meter (kV/m) was recorded; resulting in a measureable range of 50.9 dB for the peak electric field shielding measurement. Table 5 is a tabulation of the peak electric field measurements

for the composite material samples with respect to the direct strike lightning environment. Table 6 is a tabulation of comparisons of the shielding effectiveness between the various composite material samples with respect to the peak electric field meaurements due to the direct strike lightning environment. The sample with the maximum peak electric field shielding effectiveness with respect to the direct strike lightning environment was sample 3B (GFRP, wire mesh on both sides, 0.098, no paint). The peak electric field measurement was below the noise level of the measurement equipment. The sample with
the minimum peak electric field shielding effectiveness with respect to the direct strike lightning environment was sample 9B (GFRP Unitape, 0.62, no paint). A peak electric field measurement of 109.4 V/m was recorded. Therefore, a measureable range of 10.3 dB was exhibited between the maximum and minimum peak electric field shielding values for the composite material samples with respect to the direct strike lightning environment.

Test No.	Sample	Current Probe Factor	Gain (dB)	Peak Current (kA)	Peak E-Field Probe Output (mV)	Peak E-Field Probe Factor	Peak E-Field (V/m)	Correlation to Fiberglass (dB)
40	Aluminum	400 A/V	-48	68	17.1	1 V = 2 kV/m	34.2	50.9
41	Fiberglass	400 A/V	-48	68	600.0	1 V = 20 kV/m	12000.0	0.0
42	2B	400 A/V	-48	68	48.4	1 V = 2 kV/m	96.8	41.9
43	3B	400 A/V	-48	70	17.2	1 V = 2 kV/m	34.4	51.1
44	4B	400 A/V	-48	68	32.8	1 V = 2 kV/m	65.6	45.2
45	8B	400 A/V	-48	68	46.9	1 V = 2 kV/m	93.8	42.1
46	9B	400 A/V	-48	68	54.7	1 V = 2 kV/m	109.4	40.8

Table 5. Direct Strike Lightning Peak E-field Measurements.

Sample	2B	3B	4B	8B	9B
2B	-	-9.2	-3.4	-0.3	1.1
3B	9.2	-	5.9	9.0	10.3
4B	3.4	-5.9	-	3.1	4.4
8B	0.3	-9.0	-3.1	-	1.3
9B	-1.1	-10.3	-4.4	-1.3	-

Table 6. Direct Strike Lightning Peak E-field Shielding Effectiveness Comparisons.

b. The baseline for determining the maximum and minimum magnetic field rate-of-change shielding values were the same as utilized during the near strike shielding measurement test. The maximum magnetic field rate-of-change shielding baseline value was established with the aluminum panel installed on the conductive enclosure. An output signal of 16.8 mV was recorded with the B-dot sensor. The minimum magnetic field rate-of-change shielding baseline value was established with the fiberglass panel installed on the conductive enclosure. An output signal of 59.0 V was recorded; resulting in a measureable range of 70.9 dB for the magnetic field rate-of-change shielding measurement. Table 7 is a tabulation of the output signal of the B-dot sensor for the magnetic field rate-of-change measurements with respect to the direct strike lightning environment. Table 8 is a tabulation of comparisons of the shielding effectiveness between the various composite material samples with respect to the magnetic field rate-of-change measurement due to the near strike lightning environment. The sample with the maximum shielding effectiveness with respect to the magnetic field rate-of-change was sample 3A

(GFRP, wire mesh on both sides, 0.098, no paint); an output signal of 45.3 mV was measured. The sample with the minimum shielding effectiveness with respect to the magnetic field rate-of-change was sample 11A (fiberglass, 0.045, painted); an output signal of 2.4 V was measured. Therefore, a measureable range of 34.5 dB was exhibited between the maximum and minimum magnetic field rate-of-change sheilding values for the composite material samples with respect to the direct strike lightning environment.

Test No.	Sample	Current Probe Factor	Gain (dB)	Peak Current (kA)	Scope Reading (mV)	Receiver Gain (dB)	B-dot Measurement (mV)	Correlation to Fiberglass (dB)
27	Aluminum	400 A/V	-48	68	66.88	12	16.80	70.9
28	Fiberglass	400 A/V	-48	68	46.87	-42	59000.00	0.0
29	1	400 A/V	-48	69	366.00	0	366.00	44.3
30	2A	400 A/V	-48	68	225.00	0	225.00	48.4
31	3A	400 A/V	-48	68	180.34	12	45.30	62.3
32	4A	400 A/V	-48	68	197.53	6	99.00	55.5
33	5	400 A/V	-48	68	299.29	6	150.00	51.9
34	6	400 A/V	-48	68	143.66	6	72.00	58.3
35	7A	400 A/V	-48	68	215.49	6	108.00	54.7
36	8A	400 A/V	-48	68	243.42	6	122.00	53.7
37	9A	400 A/V	-48	68	84.00	0	84.00	56.9
38	9G	400 A/V	-48	68	600.00	0	600.00	39.9
39	11A	400 A/V	-48	68	602.85	-12	2400.00	27.8

Table 7. Direct Strike Lightning Magnetic Field Rate-of-Change Measurements.

Sample	1	2A	3A	4A	5	6	7A	8A	9A	9G	11A
1	-	-4.1	-18.0	-11.2	-7.6	-14.0	-10.5	-9.4	-12.7	4.4	16.5
2A	4.1	-	-13.9	-7.1	-3.5	-9.9	-6.4	-5.3	-8.6	8.5	20.6
3A	18.0	13.9	-	6.8	10.4	4.0	7.5	8.6	5.4	22.4	34.5
4A	11.2	7.1	-6.8	-	3.6	-2.8	0.8	1.8	-1.4	15.7	27.7
5	7.6	3.5	-10.4	-3.6	-	-6.4	-2.9	-1.8	-5.0	12.0	24.1
6	14.0	9.9	-4.0	2.8	6.4	-	3.5	4.6	1.3	18.4	30.5
7A	10.5	6.4	-7.5	-0.8	2.9	-3.5	-	1.1	-2.2	14.9	26.9
8A	9.4	5.3	-8.6	-1.8	1.8	-4.6	-1.1	-	-3.2	13.8	25.9
9A	12.7	8.6	-5.4	1.4	5.0	-1.3	2.2	3.2	-	17.1	29.1
9G	-4.4	-8.5	-22.4	-15.7	-12.0	-18.4	-14.9	-13.8	-17.1	-	12.0
11A	-16.5	-20.6	-34.5	-27.7	-24.1	-30.5	-26.9	-25.9	-29.1	-12.0	-

Table 8. Direct Strike Lightning Magnetic Field Rate-of-Change Shielding Effectiveness Comparisons.

3. Direct Strike Damage Test. All the composite material samples experienced varying degrees of damage due to the direct strike lightning environment consisting of an initial stroke (Component A) and a continuing current (Component C) of the idealized direct strike lightning waveform. The direct

strike damage lap joint tests are represented by tests #47 through #53. The direct strike damage butt joint tests are represented by tests #54 through #60.

a. Lap Joint Test. Table 9 is a tabulation of the direct lightning test parameters for the lap joint tests. All of the composite material samples experienced damage at the lap joint and at the point of discharge due to the application of the initial stroke (Component A) and the continuing current (Component C) direct strike lightning environment. The amount of damage varied from sample to sample dependant upon the thickness of conductive material within the composite material sample or applied on the composite material sample. Damage to the composite material samples was due to thermal stress as well as mechanical shock from the application of the initial stroke and continuing current direct strike lightning waveforms. The least amount of visual damage to the lap joint was observed on samples 2C-2D despite significant damage at the point of discharge. Samples 9C-9D and 9G-9H experienced significant lap joint damage as well as significant damage at the point of discharge. Samples 11B-11C experienced sufficient damage to preclude testing of the continuing current (low voltage) waveform. Figures B-1 through B-7 of Appendix B illustrate the damage on each set of composite material panels due to the application of the initial stroke and continuing current direct strike lightning waveform. The top picture in each of these figures represents the top surface (attachment side) of the samples, whereas the bottom picture represents the bottom surface (opposite the attachment) of the samples.

		Component A			Component C	
Test No.	Samples	Current Probe Factor	Gain (dB)	Peak Current (kA)	Peak Current (A)	Charge Transfer (C)
CAL	Aluminum	500 A/V	-57	206	X	X
47	2C-2D	500 A/V	-57	202	467	187
48	3A-3B	500 A/V	-57	202	455	182
49	4C-4D	500 A/V	-57	200	476	191
50	8C-8D	500 A/V	-57	191	470	188
51	9C-9D	500 A/V	-57	196	461	184
52	9G-9H	500 A/V	-57	199	461	184
53	11B-11C	500 A/V	-57	198	X	X

Table 9. Lap Joint Direct Strike Lightning Test Parameters.

b. Butt Joint Test. Table 10 is a tabulation of the direct lightning test parameters for the butt joint tests. All of the composite material samples experienced damage at the butt joint and at the point of discharge due to the application of the initial stroke (Component A) and the continuing current (Component C) direct strike lightning environment. Again, the amount of damage varied from sample to sample dependant upon the thickness of conductive material within the composite material sample or applied on the composite material sample. Damage to the composite material samples was due to thermal stress as well as mechanical shock from the application of the initial stroke and continuing current direct strike lightning waveforms. The least amount of visual damage to the butt joint was observed on samples 3A-3B and 8E-8F. The continuing current waveform could not be conducted on samples 2A-2B due to excessive damage to sample 2A from the initial stroke; the outer layer of sample 2A was separated from the aluminum honeycomb core. Additionally, the initial stroke current waveform was not recorded on test #54 due to disconnection of the ground cable (measurement point) as a result of the sample 2A separation of the outer layer from the aluminum honeycomb core. The continuing current waveform could not be conducted on samples 8G-8H due excessive damage to the foil bridge, which electrically connected samples 8G and 8H, from the initial stroke. Samples 11C-11D experienced sufficient damage to preclude testing of the continuing current (low voltage) waveform. Figures C-1 through C-9 of Appendix C illustrate the damage on each set of composite material panels due to the application of the initial stroke and continuing current direct strike lightning waveform. On the figures with two view sets, the top picture in each of these figures represents the top surface (attachment side) of the samples, whereas the bottom picture represents the bottom surface (opposite the attachment) of the samples.

		Component A			Component C	
Test No.	Samples	Current Probe Factor	Gain (dB)	Peak Current (kA)	Peak Current (A)	Charge Transfer (C)
CAL	Aluminum	500 A/V	-57	X	547	190
54	2C-2D	500 A/V	-57	X	X	X
55	3A-3B	500 A/V	-57	203	467	187
56	4E-4F	500 A/V	-57	203	482	193
57	8E-8F	500 A/V	-57	198	461	184
58	8G-8H	500 A/V	-57	195	X	X
59	9E-9F	500 A/V	-57	195	465	186
60	11C-11D	500 A/V	-57	196	X	X

Table 10. Butt Joint Direct Strike Lightning Test Parameters.

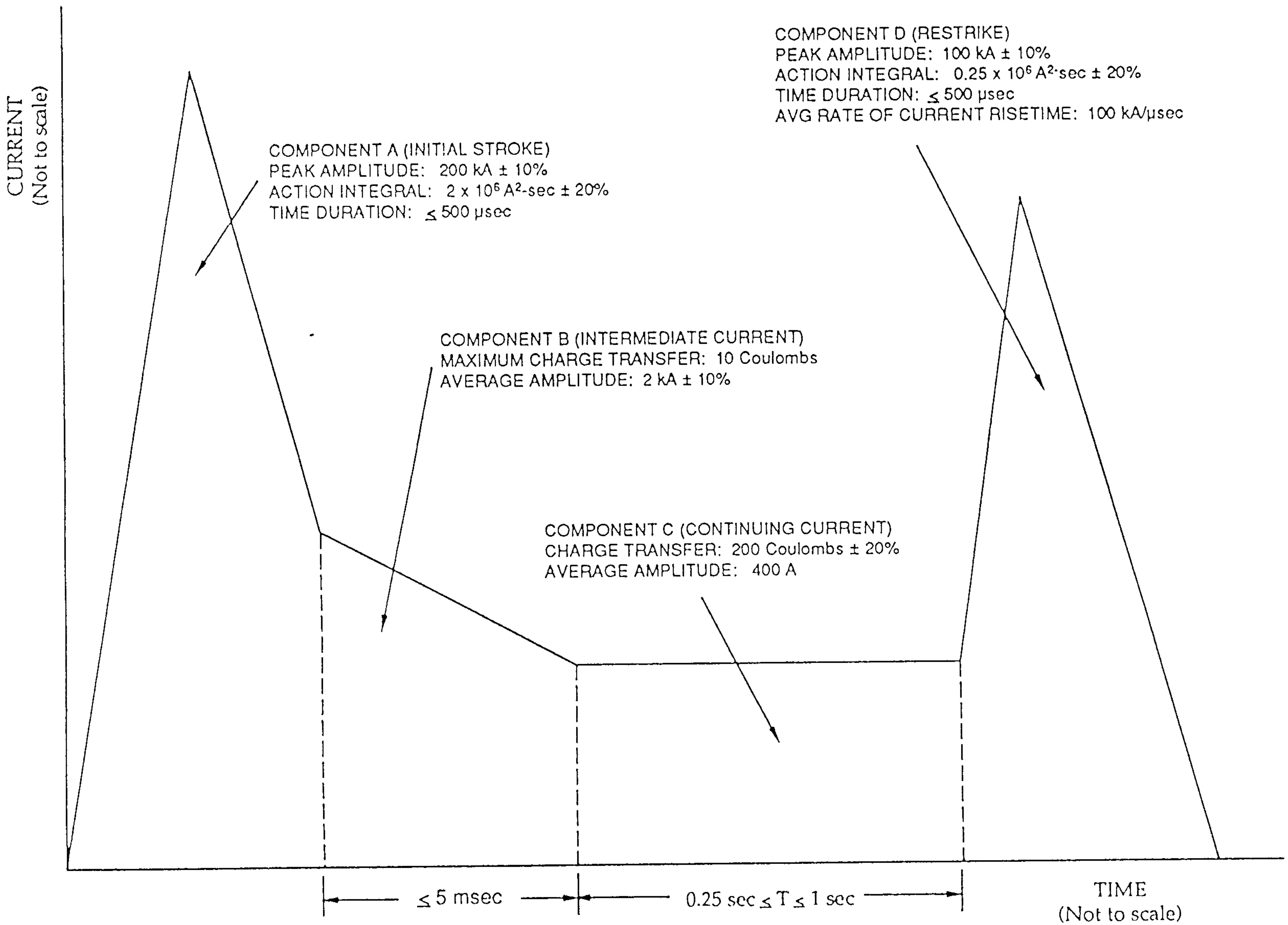


Figure 1. Idealized Direct Strike Lightning Waveform.

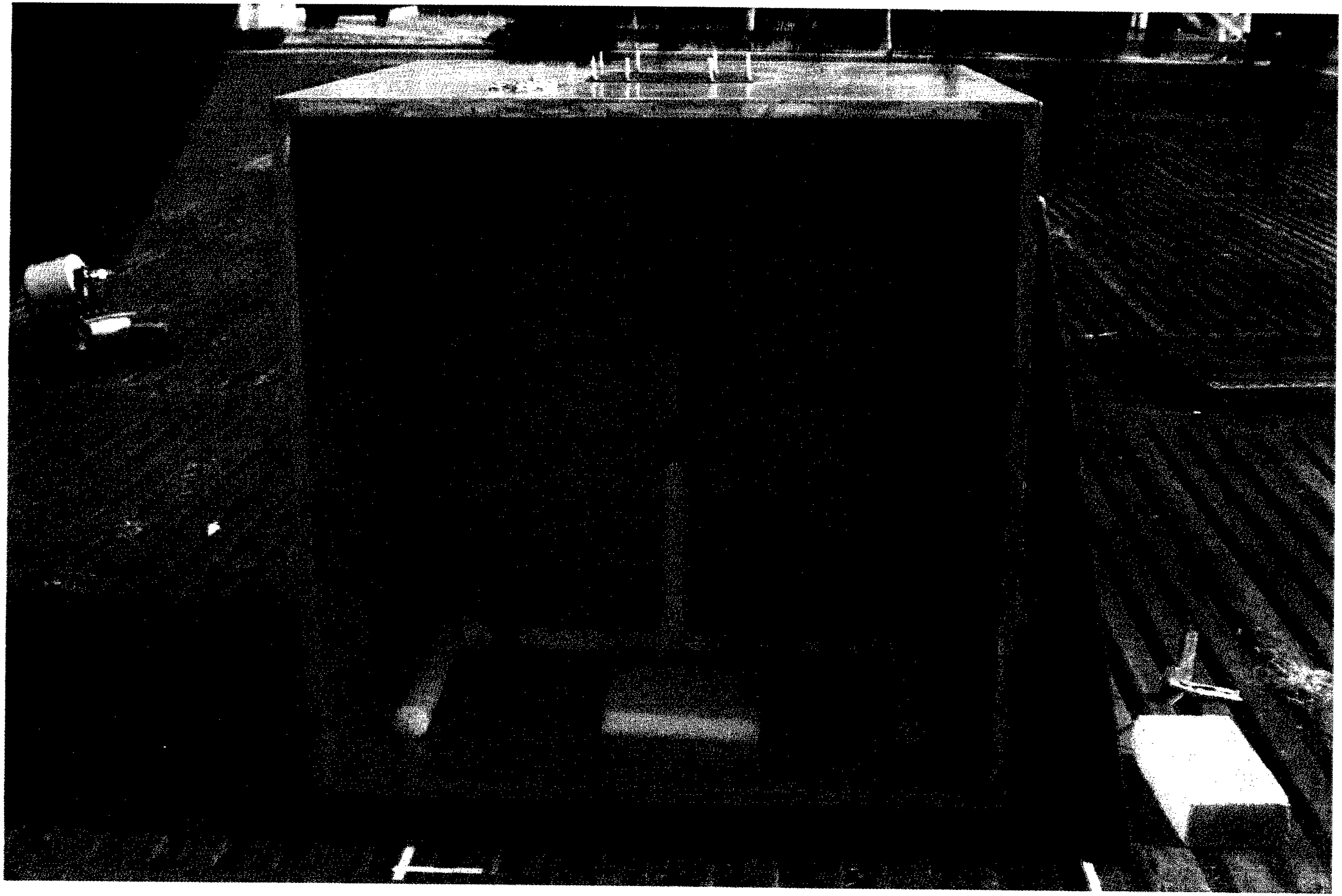


Figure 2. Peak Electric Field Sensor Installed in Conductive Enclosure.

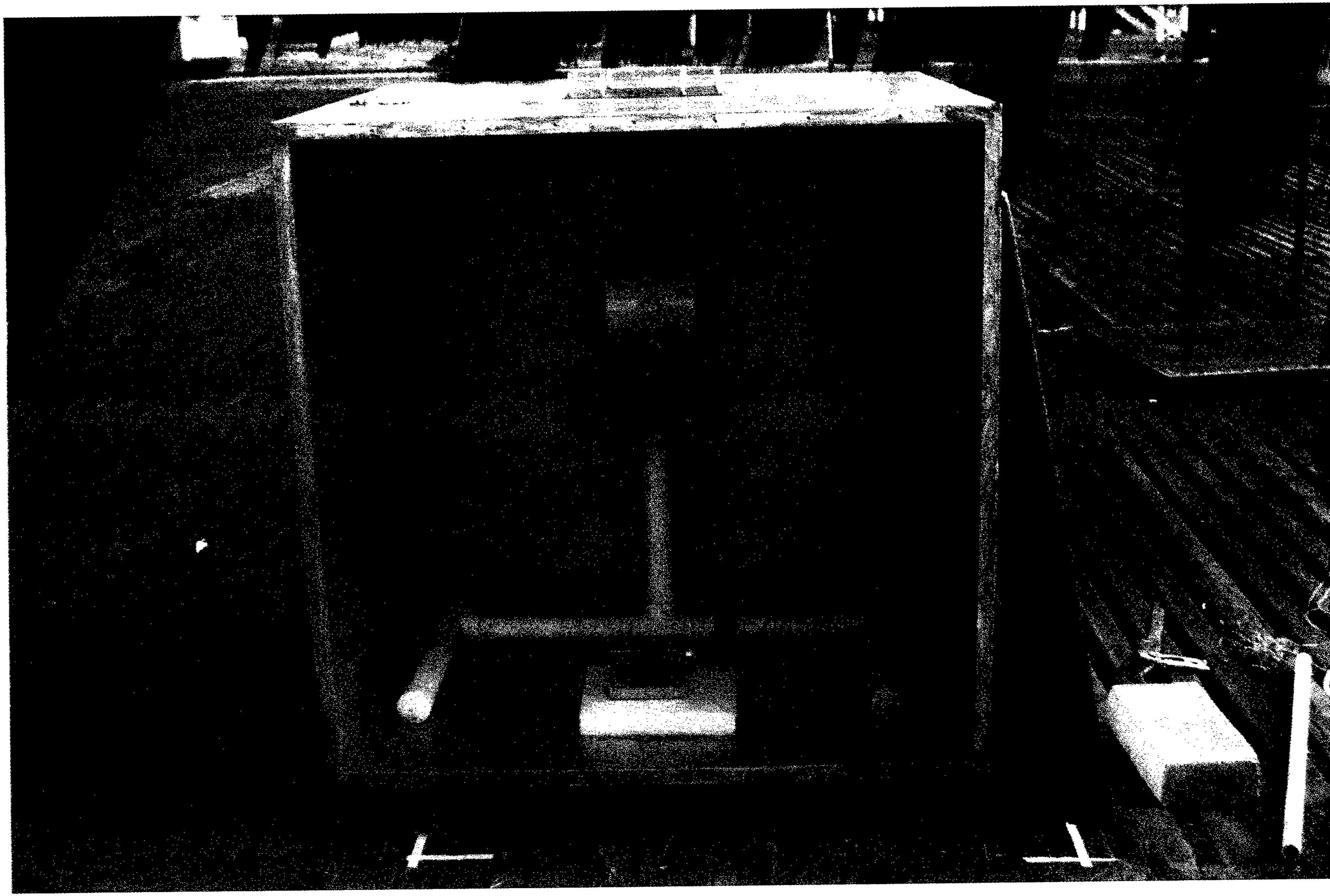


Figure 3. B-dot Sensor Installed in Conductive Enclosure.

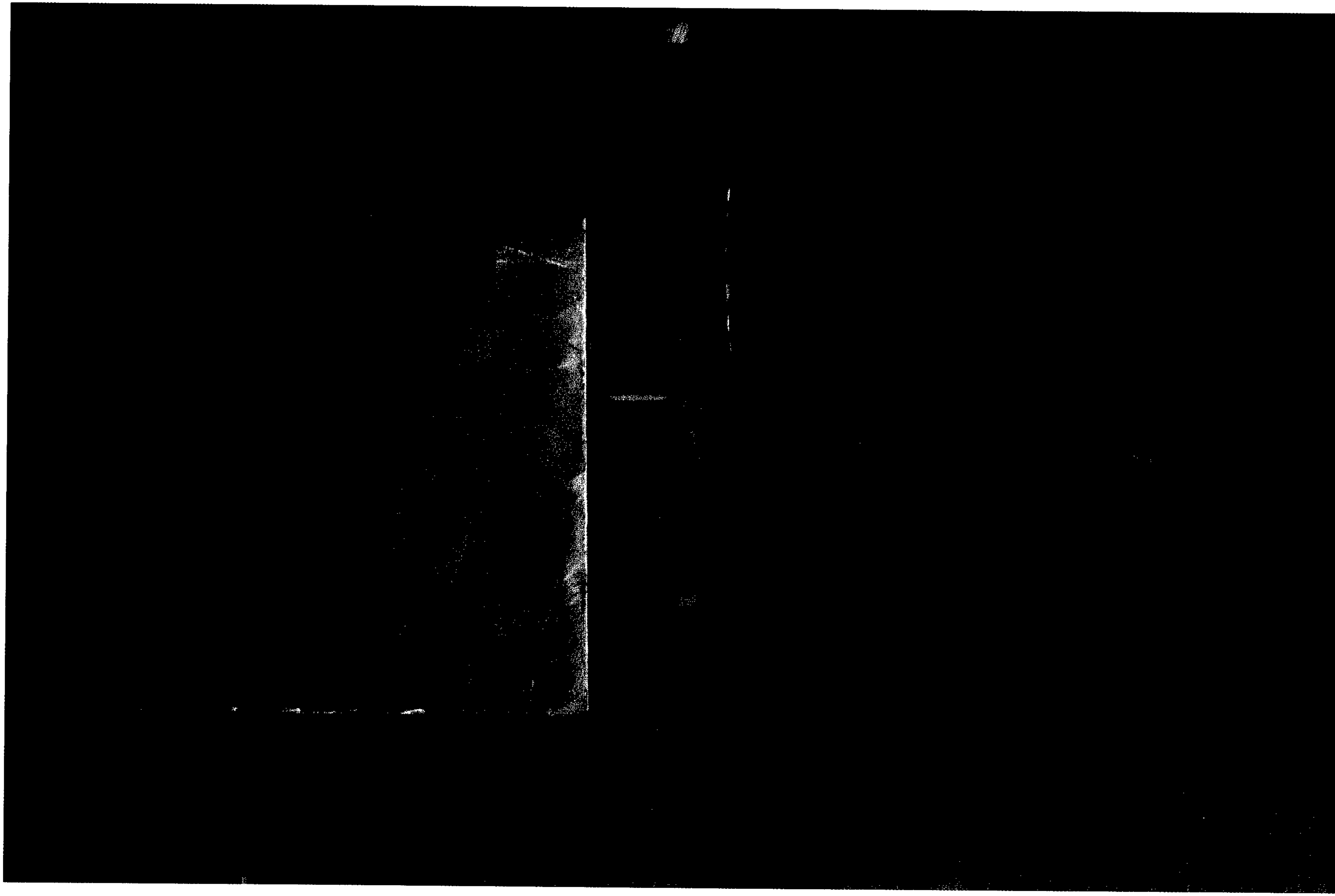


Figure 4. Test Setup for Direct Strike Shielding Effectiveness Measurement.

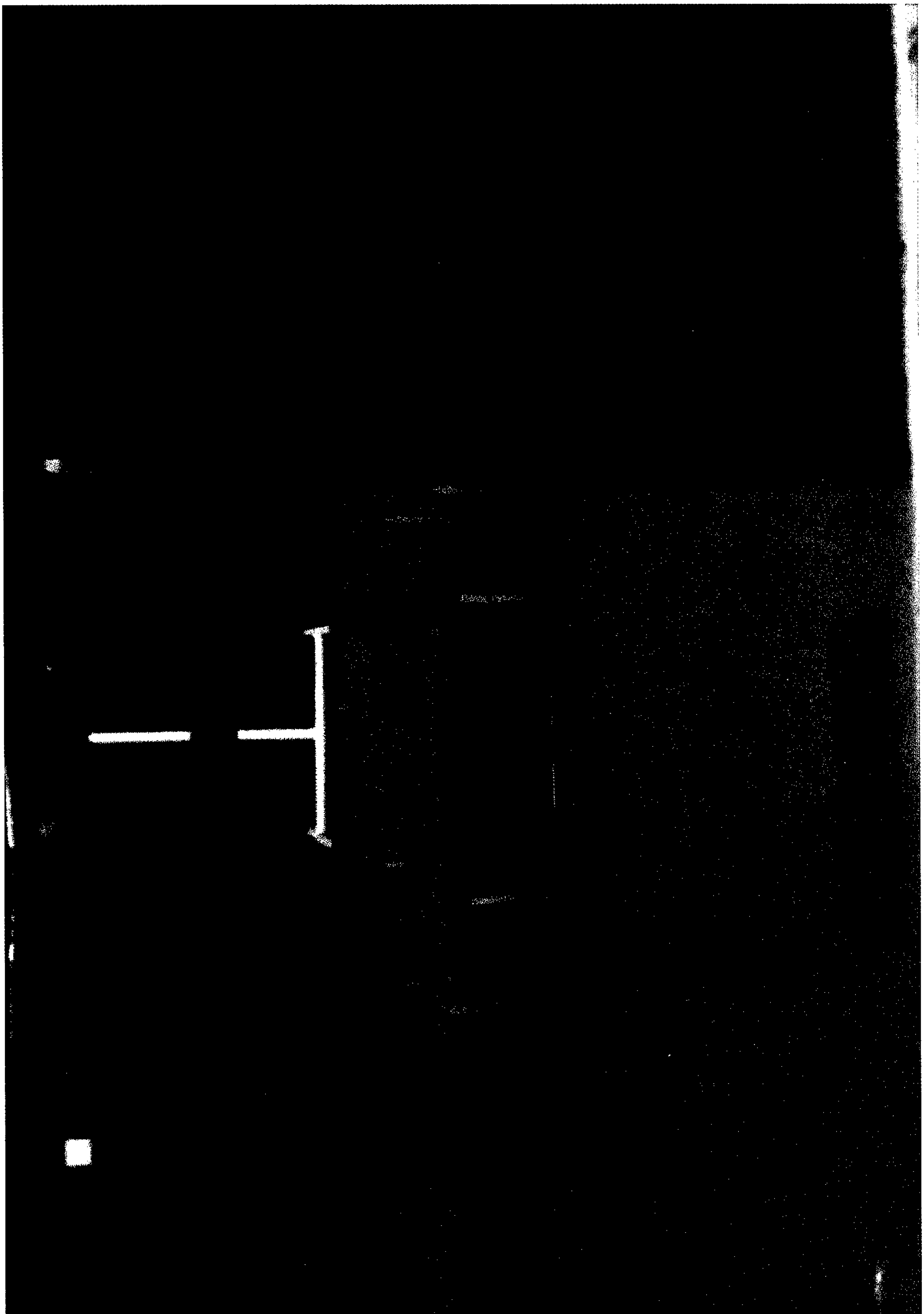


Figure 5. Leader Wire Positioned on Composite Material Tile.

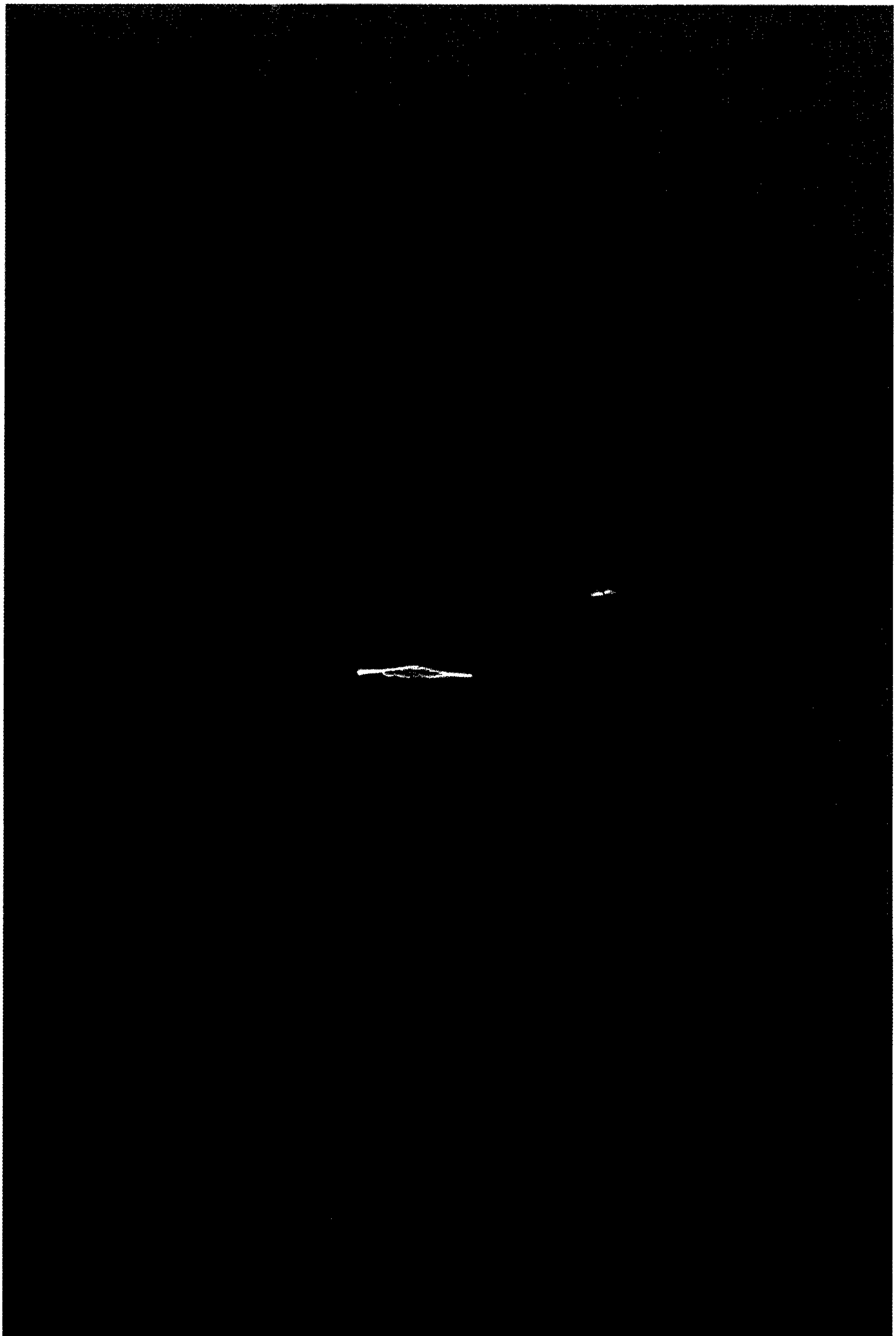


Figure 6. Direct Strike (Component D) to Conductive Enclosure

Figure 7. Test Setup for Direct Strike Damage Test.

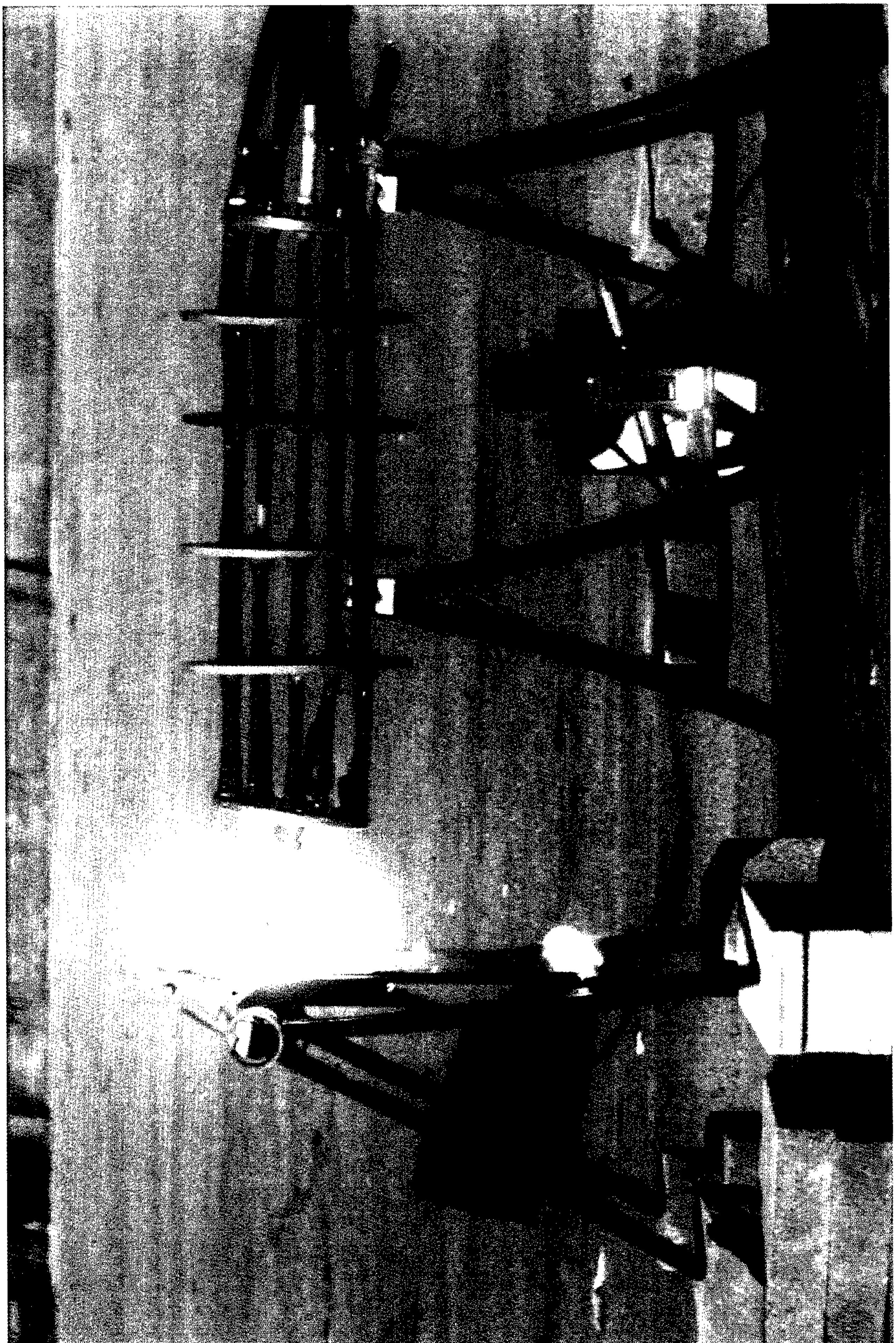


Figure 8. Direct Strike (Component A) to Composite Material Tile.

APPENDIX A

TEST PLAN

LIGHTNING EFFECTS ON COMPOSITE MATERIALS

ROSS W. EVANS
TEC-MASTERS, INC.
HUNTSVILLE, ALABAMA

SEPTEMBER 27, 1996

PREPARED FOR NASA - MARSHALL SPACE FLIGHT CENTER

CONTRACT NO. NAS8-39983

LIGHTNING TEST PLAN

1. Introduction

Simulated lightning tests will be performed on special square or rectangular samples of composite materials. Some tests will be made on single samples; others will be made on joints between two samples.

2. Purpose

The purpose of this test program is to determine how composite material is affected when it is struck by lightning. Direct effects to the material and to joints between samples will be evaluated by inspection of the simulated lightning contact point and the mating surfaces.

Indirect effects will be evaluated by measuring electromagnetic fields within a conductive enclosure when one side of the enclosure contains a panel of composite material that is struck by lightning.

3. Description of Test Samples

Single Squares -- Samples will be made with woven graphite mats and unidirectional graphite tape in epoxy resin. Some samples will have a top layer of metal screen. There will also be samples with a honeycomb aluminum core with graphite epoxy mats on top and bottom. The samples will have sawed edges, and in some cases one inch wide strips around the outer edge of the surface will be sanded to expose the conductive filler. Opposite edges of all samples will be spot painted with conductive paint to facilitate resistivity measurements. For some tests, the sanded strips on the surfaces will be painted with conductive paint to provide a uniform contact to the graphite fibers. Two holes in each of the four edges will allow bolting the samples to the conductive enclosure for indirect effects measurements. They will also provide a method of bolting the edges of samples together so tests on joints can be made. Special samples of glass epoxy or other nonconductive material with and without conductive paint applied will be used for certain tests.

Lap Joints -- Two single samples will be joined with the one inch wide surfaces mated. In some cases these surfaces will be sanded and painted with conductive paint to provide a uniform, more conductive, contact. The samples will be held together with electrically isolated bolts.

Butt Joints -- Two samples with edges butted together will be joined by an aluminum doubler plate bolted to the one inch wide strip on each sample. Bolts will be electrically isolated. Some samples will have conductive paint on sanded surfaces as they were in the samples with lapped joints.

4. Description of Tests

Resistivity Tests -- Paint spots on two opposite edges of each sample with silver paint to obtain good contact with the conductive filler. Measure edge to edge of each sample to determine resistance.

Measure the resistance across lap joints from the conductive paint spot or strip on one sample to the conductive paint spot or strip on the adjoining sample. Measure resistance across butt joints from the conductive paint on one sample to the conductive paint on the other sample. Measure resistance from each conductive paint spot or strip to the aluminum sheet used as a doubler across the joint.

Simulated lightning tests -- The criteria for the simulated lightning strike will be taken from NSTS-07636. Since this is a general test of composite materials that may be used anywhere on a space vehicle, it is assumed that it may be subjected to the most severe lightning environment. The simulated lightning strike is broken into four components. Component A consists of a 200 kA peak and a 2×10^6 A^2s action integral, component B has a 2 kA peak and

10 Coulombs, component C has a 400 A peak and 200 Coulombs, and component D has a 100 kA peak with a 0.25×10^6 A^2s action integral. Different combinations of components are usually used to represent a strike to a particular vehicle depending upon the location of the strike, speed of the vehicle, configuration, etc. We will use the most severe components but will limit the number to reduce testing. For planning purposes I assumed components A, C, & D will be used. Component D will give the fast rise time that produces high frequency for radiated or induced field strength measurements. Component A produces a high current shock effect, and component C will deliver the heating effect.

The tests will be performed on the various samples in two different configurations. The first test configuration will consist of 12 inch square samples of material with silver paint covering a one inch wide strip around the edge of the bottom surface. Each sample will be mounted over an opening in a steel enclosure. The silver paint surface will be in contact with the enclosure. Simulated lightning Component D should be used for each test. The simulated lightning strike will be directed to ground nearby. The electric and magnetic fields inside the enclosure will be monitored one at a time to determine relative field strength between samples.

A second test in this configuration will direct the strike to the top surface of the sample. Thin samples will be used in some cases, and full lightning strike simulations would burn through the material. The peak currents and time will be limited to provide relative amplitude data on fields transmitted through the material rather than direct effects on the material. If damage to the samples prevents their use more than once, only the electric field will be monitored. At least one test will be made to each of the different samples including a nonconductive sample with just enough conductive paint to lead the strike to the center.

The second test configuration will have a silver painted strip along an edge of one sample mated to a similar silver painted strip along an edge of another sample. They will be mated through a lap joint, through an aluminum plate bridge across a butt joint, and through a foil bridge across a butt joint. Nylon screws or insulated metal screws will be used to avoid contact except through the mating surfaces of the samples. Simulated lightning components A and C should be used for each test. The simulated strike will be directed to the center of one sample, and the other sample will be grounded through a silver painted surface. This will allow the high currents to flow through the joint. The mating surfaces as well as the top surface will be inspected to determine damage. At least one strike will be made to each of the different types of samples with lap joints and again with butt joints with an aluminum plate bridge. One other strike will be made to GFRP mat samples using a butt joint with aluminum foil as a bridge.

LIGHTNING TEST RECAP

1. Single sample, remote strike:

Mount a field strength detector within a conductive (steel) enclosure with a ten inch square aperture.

Mount single samples over the opening.

Direct a simulated lightning strike, component "D" (fast rise time),.to ground near the sample.

Measure field strength and compare data between samples.

Measure electric field and magnetic field separately.

This will require at least two strikes per sample.

2. Single sample, direct strike:

Mount an electric field strength detector within the enclosure.

Mount single samples over the opening.

Strike the center of each sample with simulated lightning strike component "D".

Measure field strength and compare data between samples.

If samples are reusable repeat the test with a magnetic sensor in the enclosure.

3. Two samples with lapped joint:

Join two samples of the same type material by overlapping approximately one inch wide mating surfaces.

Use nonconductive or insulated bolts at the joint.

Connect the opposite edge of one sample to the return.

Strike the center of the other sample with simulated lightning strike Components "A" and "C" (high current).

Inspect the joint as well as the top surface and compare damage between types of material.

4. Two samples with butted joint and aluminum plate bridge:

Join two samples of the same type material by butting edges together and bridging the seam with an aluminum plate.

Use nonconductive or insulated bolts at both joints.

Connect the opposite edge of one sample to the return.

Strike the center of the other sample with simulated lightning strike components "A" and "C".

Inspect the joints as well as the top surface and compare damage between types of material.

5. Two samples with butted joint and aluminum foil bridge:

Join two samples of Graphite Filament Reinforced Plastic (GFRP) mat material by butting edges together and bridging the seam with aluminum foil.

Foil will be mated to sanded, silver painted edges using silver paint as an adhesive.

A nonconductive fiberglass bridge may be attached to the back side of the joint as a mechanical stiffener.

Connect the opposite edge of one sample to the return.

Strike the center of the other sample with simulated lightning strike components "A" and "C".

Inspect the joint as well as the top surface and compare damage between types of material.

6. Test Samples:

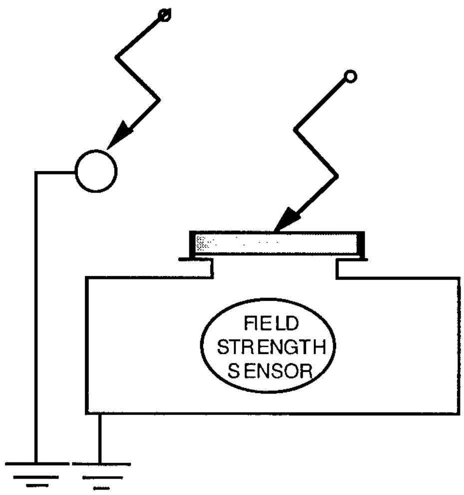
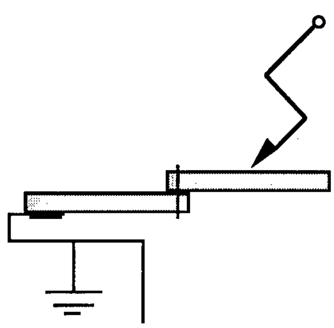
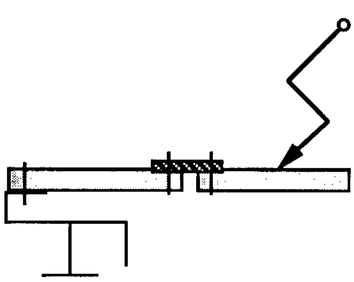
Tests described in paragraphs 1, 2, 3, and 4 will be performed on the following samples:

Nonconductive fiberglass epoxy with silver paint
GFRP Mats
GFRP Unitape
Aluminum honeycomb core in GFRP
Wire mesh on top of GFRP
Wire mesh on top and bottom of GFRP

The test described in paragraph 5 will be performed on GFRP mat samples only.

Solid metal and nonconductive panels will be tested for comparison where required.

LIGHTNING TESTS

TEST SETUP	TEST NUMBER & DESCRIPTION
	Single Sample 1 and 2. Painted 1" Strip Along Edge of Bottom Surface Mounted to Grounded Steel Box. Strike directed to separated ground terminal and to center of sample.
	Lap Joints 3. Painted 1" Strip Along One Edge of Bottom Surface Mounted to Grounded Bracket. Painted Strip Along Opposite Edge of Top Surface Mounted to Painted Strip on Bottom of Other Sample.
	Butt Joints 4 and 5. Painted 1" Strip Along One Edge of Bottom Surface Mounted to Grounded Bracket. Painted Strip Along One Edge of Top Surface of Two Samples Joined Thru Aluminum Plate and Thru Aluminum Foil.

TEST LIST

1 and 2. -- Field Strength Tests:

All samples except fiberglass and steel plate have silver paint on sanded edges around bottom to mate with aluminum or steel box.

1. 1/8″ to 1/4″ thick metal plate
2. Nonconductive fiberglass
3. Nonconductive fiberglass with whole bottom painted
4. GFRP mats
5. GFRP unitape
6. Aluminum honeycomb core in GFRP
7. Wire mesh on top of GFRP
8. Wire mesh on top and bottom of GFRP

3. -- Lap Joint Tests:

Lapped joints between samples of the same type. All have sanded, painted mating surfaces except # 7 which is sanded only.

1. Nonconductive fiberglass - whole surfaces painted
2. GFRP mats
3. GFRP unitape
4. Aluminum honeycomb core in GFRP
5. Wire mesh on top of GFRP
6. Wire mesh on top and bottom of GFRP
7. GFRP mats - sanded, no paint on edges

4 and 5. -- Butted Joint Tests:

All have sanded, painted edges mated to an aluminum plate bridge, except # 6 which uses an aluminum foil bridge.

1. GFRP mats
2. GFRP unitape
3. Aluminum honeycomb core in GFRP
4. Wire mesh on top of GFRP
5. Wire mesh on top and bottom of GFRP
6. GFRP mats - aluminum foil bridge
7. Painted fiberglass

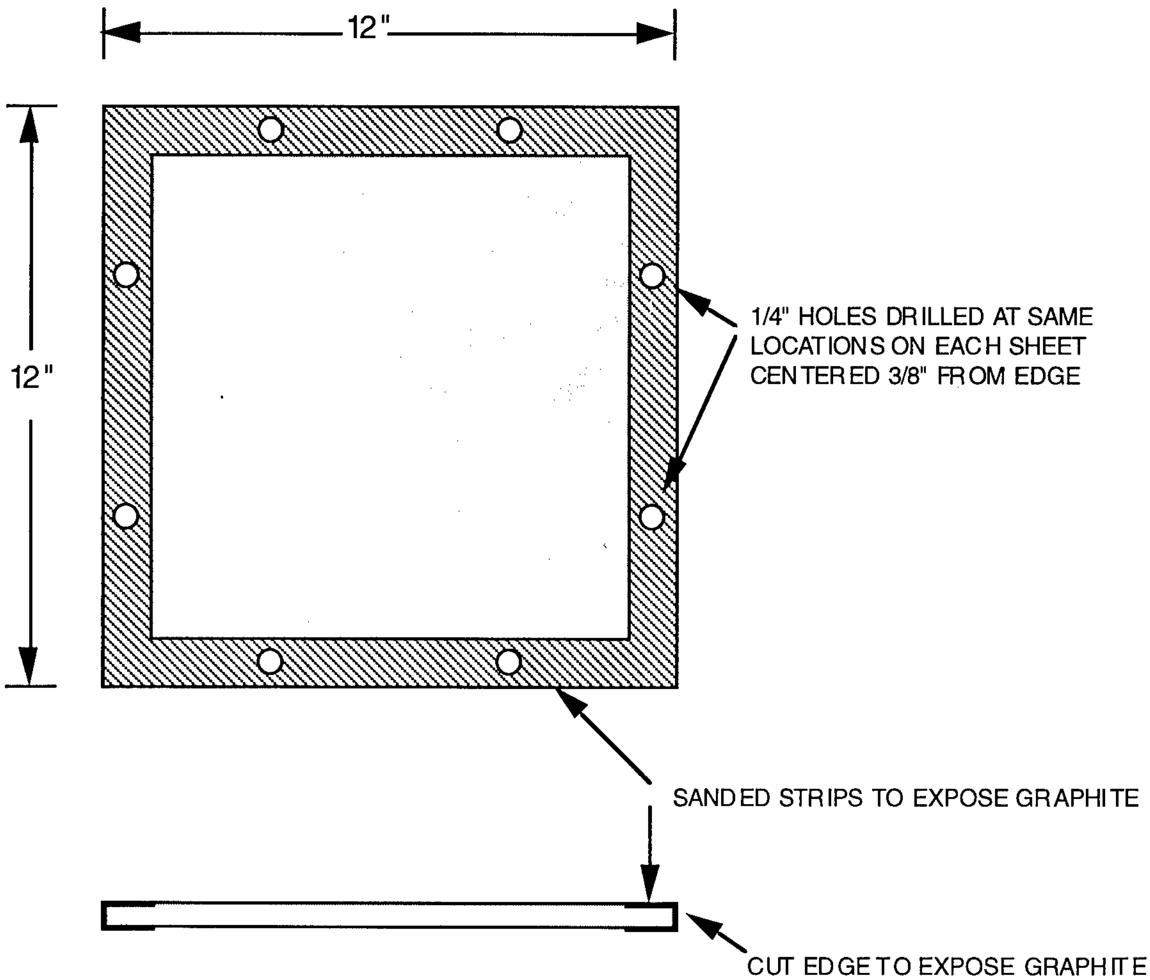


Figure 1. - Test Sample

TEST SAMPLES

All samples will be 12″ by 12″, with a 3/4″ to 1″ wide strip sanded on the top surface next to all edges to expose conductive filler, All edges will be sawed to obtain correct size and to expose conductive filler. Two 1/4″ holes will be drilled near each of the four edges. The holes will be in the same location on each sample. This will allow joining two samples through the sanded surfaces. Samples will include the following:

7 - Graphite filament mat
5 - Graphite filament unitape
5 - Honeycomb aluminum with graphite mats on top and bottom
3 - Nonconductive epoxy, no conductive filler or sanded edges
3 - GFRP mat with screen on top
2 - GFRP mat with screen on top and bottom

SAMPLE vs TEST

SAMPLE		REMOTE STR.		DIRECT STR.		JOINT		PAINT #			
Type	No.	E	M	M	E	Lap	Butt	All	4 edges	2 edges	None
Aluminum	x	x	x	x	x						
Honeycomb 0.730	1	1	1	1					1		
Honeycomb 0.621	2a,b	2a	2a	2a	2b				2		
Honeycomb 0.621	2c,d					2c,d	2a,b			2	
Wire, two sides	3a,b	3a	3a	3a	3b	3a,b	3a,b				2
Wire, one side	4a,b	4a	4a	4a	4b				2		
Wire, one side	4c,d,e,f,g					4c,d	4e,f			4	1
GFRP 0.160	5	5	5	5					1		
GFRP 0 .130	6	6	6	6					1		
GFRP 0 .080	7a,b	7a	7a	7a					2		
GFRP 0.068	8a,b	8a	8a	8a	8b				2		
GFRP 0.068	8c,d,e,f					8c,d	8e,f			4	
GFRP 0.068	8g,h						8g,h*			2	
GFRP Unitape	9a,b	9a	9a	9a	9b				2		
GFRP Unitape	9c,d,e,f					9c,d	9e,f			4	
GFRP Unitape	9g,h	9g	9g	9g		9g,h					2
Fiberglass 0.060	10a,b,c	10a	10a	10a	10b						4
Fiberglass 0.045	11a,b,c,d	11a	11a	11a		11b,c	11a,d	4			
* Aluminum foil bridge attached with silver paint.											

NOTES

1. Remote strike electric field and magnetic field tests to be performed on each of thirteen samples. If there is no difference between results using aluminum plate and unpainted fiberglass, skip the rest of the remote strike tests.

2. Direct strike tests will measure magnetic field using each of thirteen samples and electric field using seven samples as noted. Expect damage to all samples.

3. Lap joint tests will be made on seven pairs of samples. May reuse reversed samples where strike is to fresh point and new edges are mated. Also includes test on one GFRP unitape sample with no painted edges.

4. Butt joint tests will be performed on seven pairs of samples. May reuse reversed samples where strike is to fresh point and new edges are mated.

FIELD STRENGTH, REMOTE STRIKE (RS)

Electric Field

Test No.	Sample Description	Sample No.
1.	Aluminum Plate	-
2.	Fiberglass Plate (0.060)	10A
3.	Honeycomb (0.730)	1
4.	Honeycomb (0.621)	2A
5.	Wire, Both Sides (0.098)(No Paint)	3A
6.	Wire, Top Side (0.073)	4A
7.	GFRP Mat (0.160)	5
8.	GFRP Mat (0.130)	6
9.	GFRP Mat (0.080)	7A
10.	GFRP Mat (0.068)	8A
11.	GFRP Unitape (0.062)	9A
12.	GFRP Unitape (0.062)(No Paint)	9G
13.	Fiberglass, Painted (0.045)	11A

Magnetic Field Rate of Change

Test No.	Sample Description	Sample No.
14.	Aluminum Plate	-
15.	Fiberglass Plate (0.060)	10A
16.	Honeycomb (0.730)	1
17.	Honeycomb (0.621)	2A
18.	Wire, Both Sides (0.098)(No Paint)	3A
19.	Wire, Top Side (0.073)	4A
20.	GFRP Mat (0.160)	5
21.	GFRP Mat (0.130)	6
22.	GFRP Mat (0.080)	7A
23.	GFRP Mat (0.068)	8A
24.	GFRP Unitape (0.062)	9A
25.	GFRP Unitape (0.062)(No Paint)	9G
26.	Fiberglass, Painted (0.045)	11A

FIELD STRENGTH, DIRECT STRIKE (DS)

Magnetic Field Rate of Change

Test No.	Sample Description	Sample No.
27.	Aluminum Plate	-
28.	Fiberglass Plate (0.060)	10A
29.	Honeycomb (0.730)	1
30.	Honeycomb (0.621)	2A
31.	Wire, Both Sides (0.098)(No Paint)	3A
32.	Wire, Top Side (0.073)	4A
33.	GFRP Mat (0.160)	5
34.	GFRP Mat (0.130)	6
35.	GFRP Mat (0.080)	7A
36.	GFRP Mat (0.068)	8A
37.	GFRP Unitape (0.062)	9A
38.	GFRP Unitape (0.062)(No Paint)	9G
39.	Fiberglass, Painted (0.045)	11A

Electric Field

Test No.	Sample Description	Sample No.
40.	Aluminum Plate	-
41.	Fiberglass Plate (0.060)	10B
42.	Honeycomb (0.621)	2B
43.	Wire, Both Sides (0.098)(No Paint)	3B
44.	Wire, Top Side (0.073)	4B
45.	GFRP Mat (0.068)	8B
46.	GFRP Unitape (0.062)	9B

JOINT TEST, DIRECT STRIKE

(A and C Components Separate)

Lap Joint

Test No.	Sample Description	Sample No.	
47.	Honeycomb (0.621)	2C-2D	
48.	Wire, Both Sides (0.098)(No Paint)	3A-3B	Reuse
49.	Wire, Top Side (0.073)	4C-4D	
50.	GFRP Mat (0.068)	8C-8D	
51.	GFRP Unitape (0.062)	9C-9D	
52.	GFRP Unitape (0.062)(No Paint)	9G-9H	
53.	Fiberglass, Painted (0.045)	11B-11C	(No C comp.)

Butt Joint

Test No.	Sample Description	Sample No.	
54.	Honeycomb (0.621)	2A-2B	Reuse (No C comp)
55.	Wire, Both Sides (0.098)(No Paint)	3A-3B	2nd Reuse
56.	Wire, Top Side (0.073)	4E-4F	
57.	GFRP Mat (0.068)	8E-8F	
58.	GFRP Mat (0.068) (Foil Bridge)	8G-8H	(No C comp.)
59.	GFRP Unitape (0.062)	9E-9F	
60.	Fiberglass, Painted (0.045)	11A-11D	One reused (No C comp.)

APPENDIX B

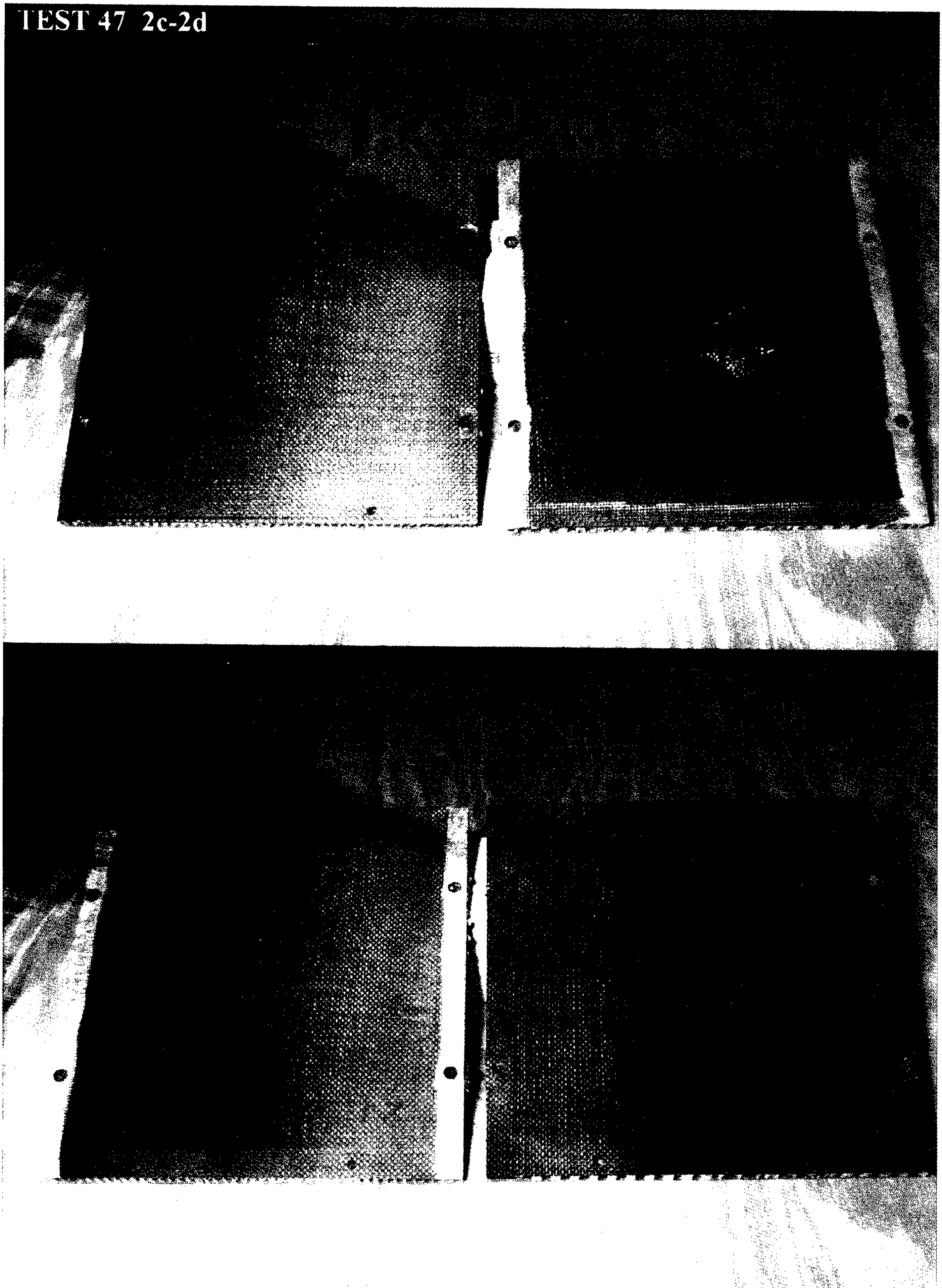


Figure B–1. Direct Strike Damage to Tiles 2c and 2d (Test # 47).

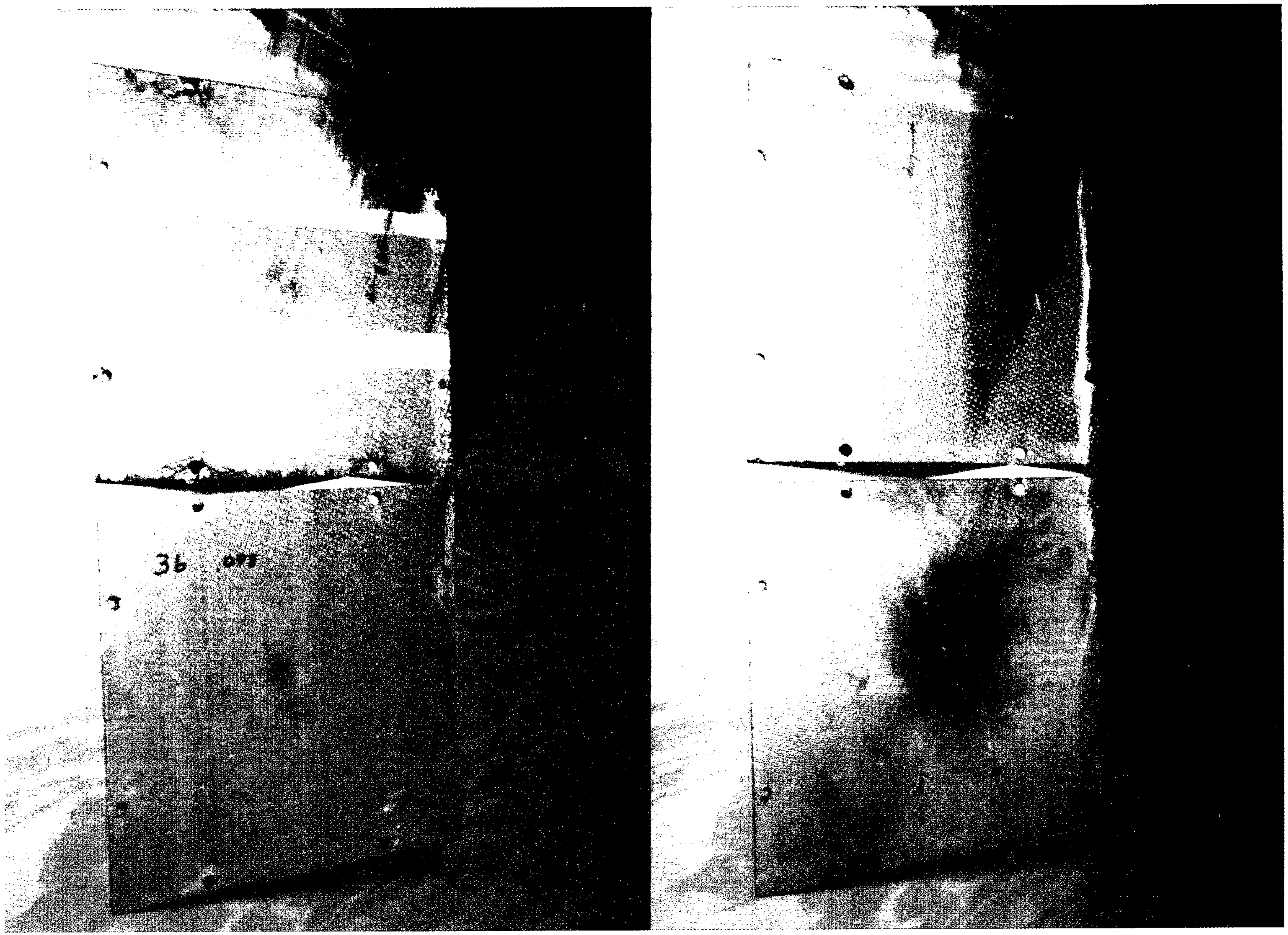


Figure B–2. Direct Strike Damage to Tiles 3a and 3b (Test # 48).

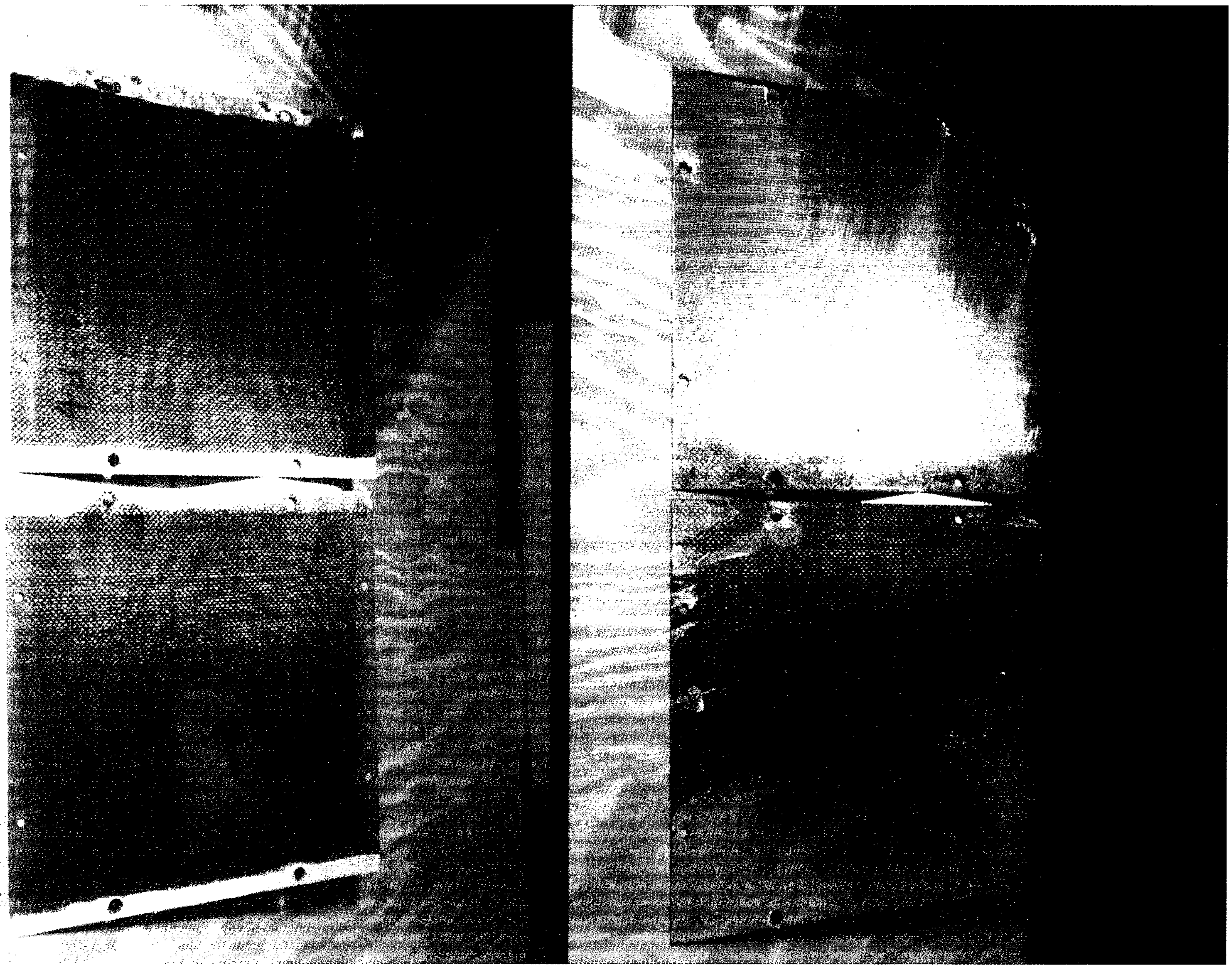


Figure B–3. Direct Strike Damage to Tiles 4c and 4d (Test # 49).

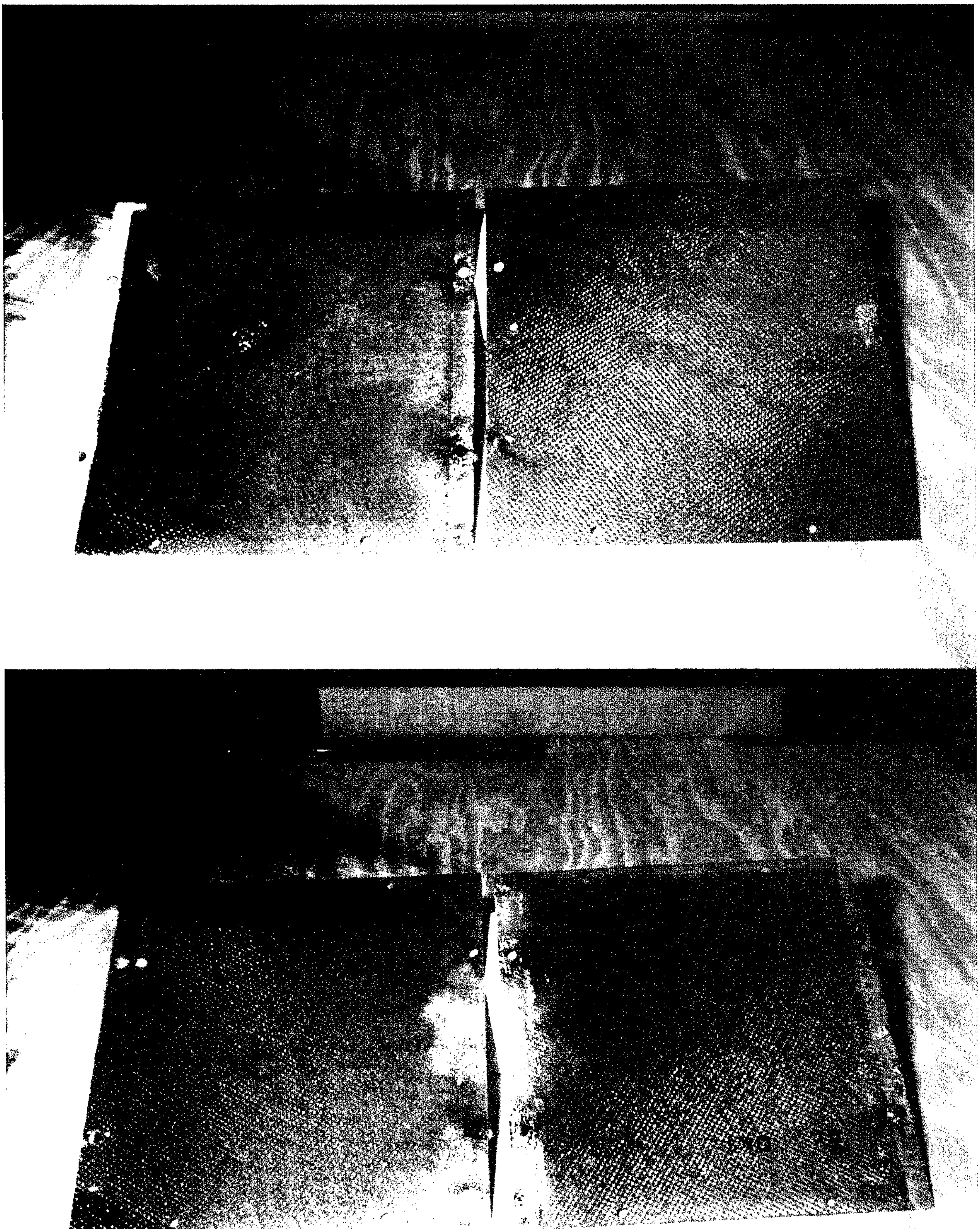


Figure B–4. Direct Strike Damage to Tiles 8c and 8d (Test # 50).

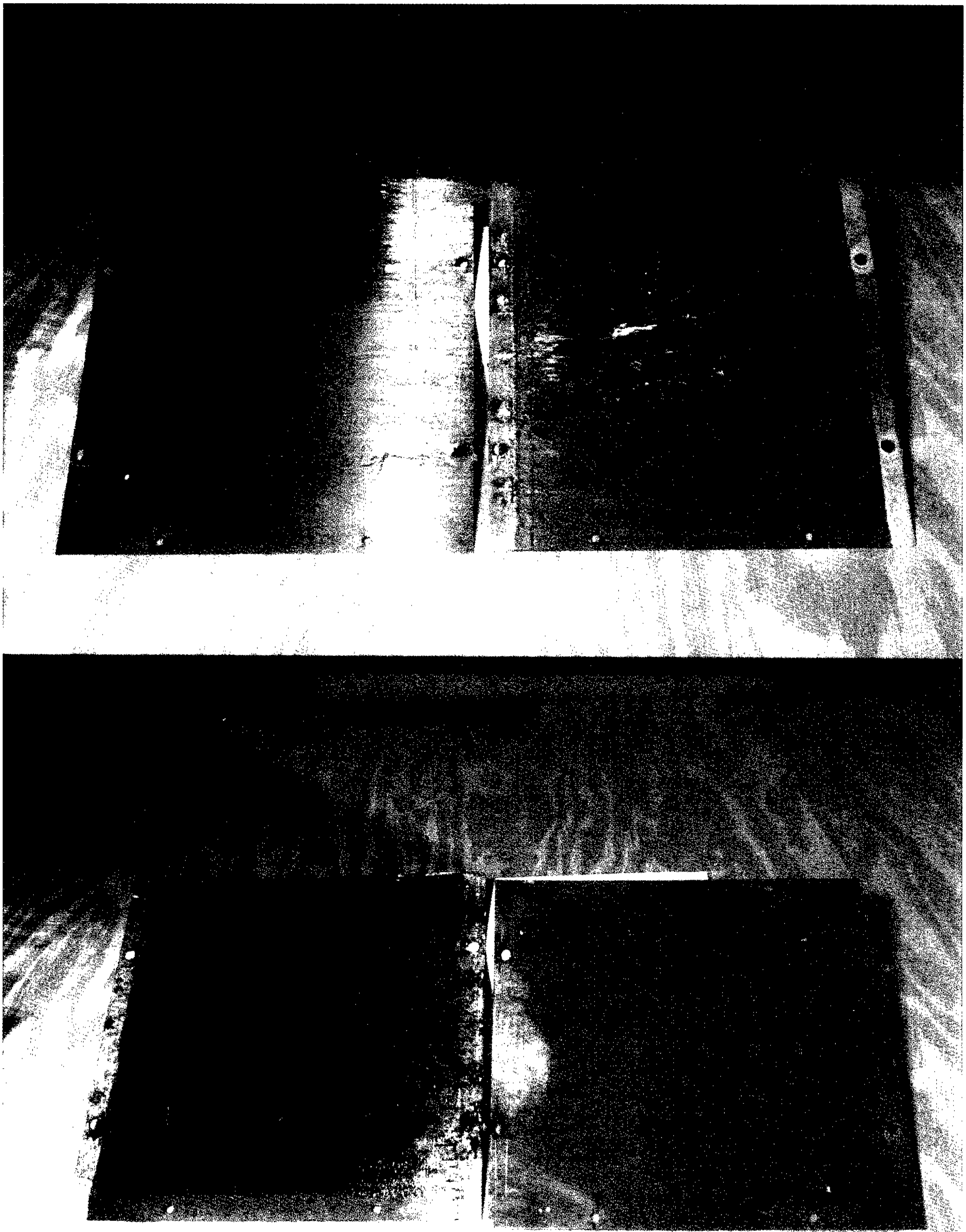


Figure B–5. Direct Strike Damage to Tile 9c and 9d (Test # 51).

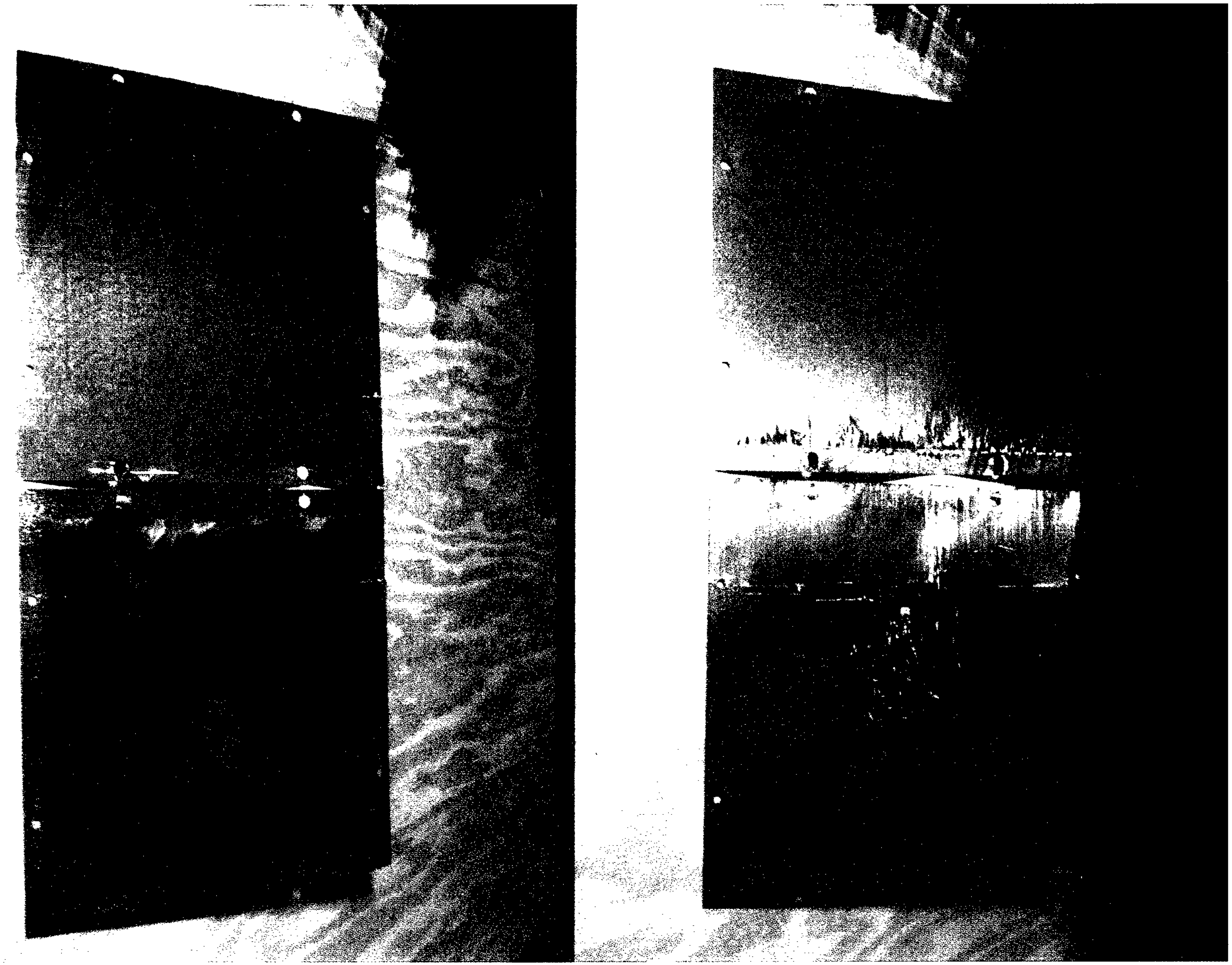


Figure B–6. Direct Strike Damage to Tiles 9g and 9h (Test # 52).

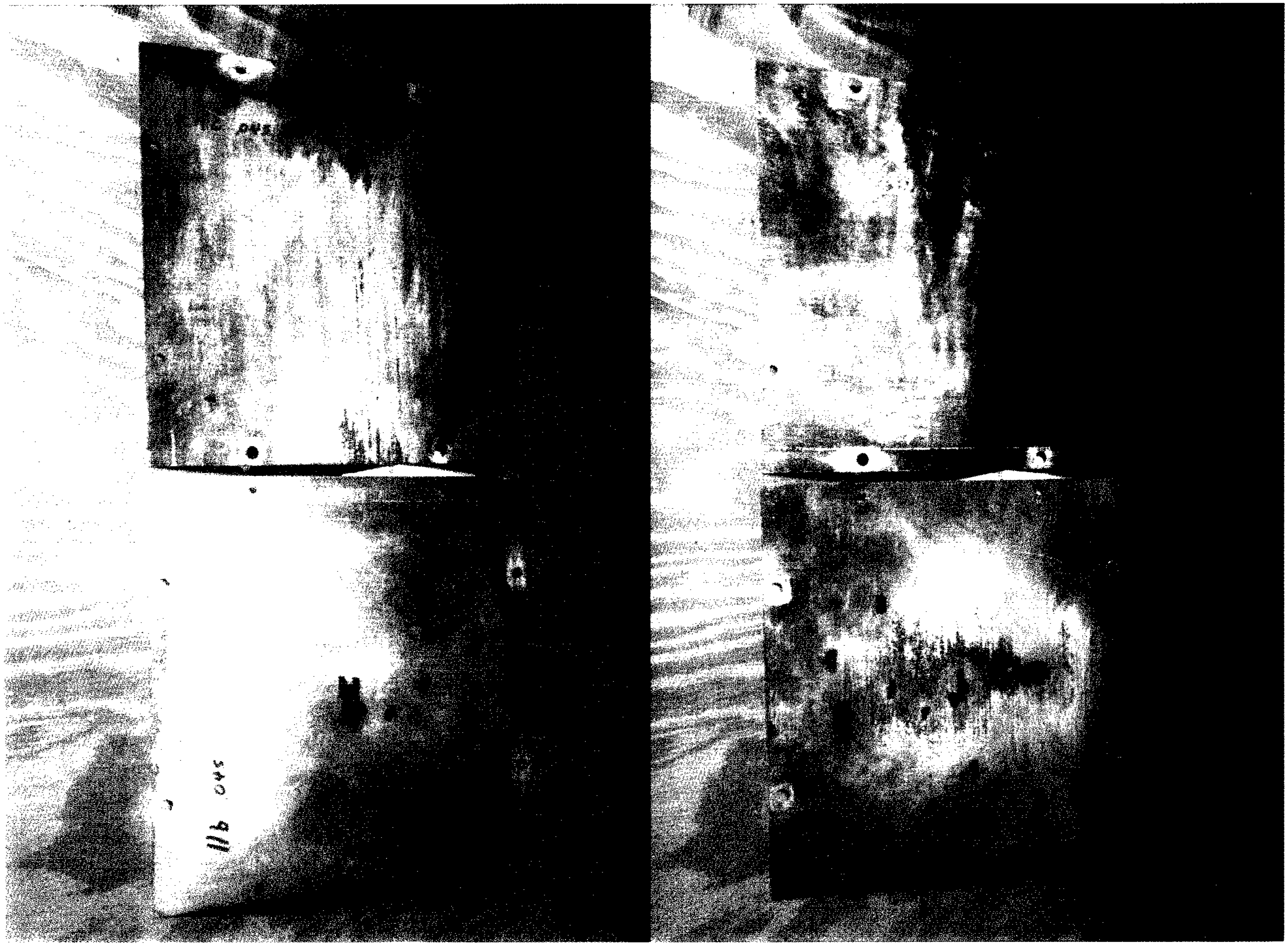


Figure B–7. Direct Strike Damage to Tiles 11b and 11c (Test # 53).

APPENDIX C

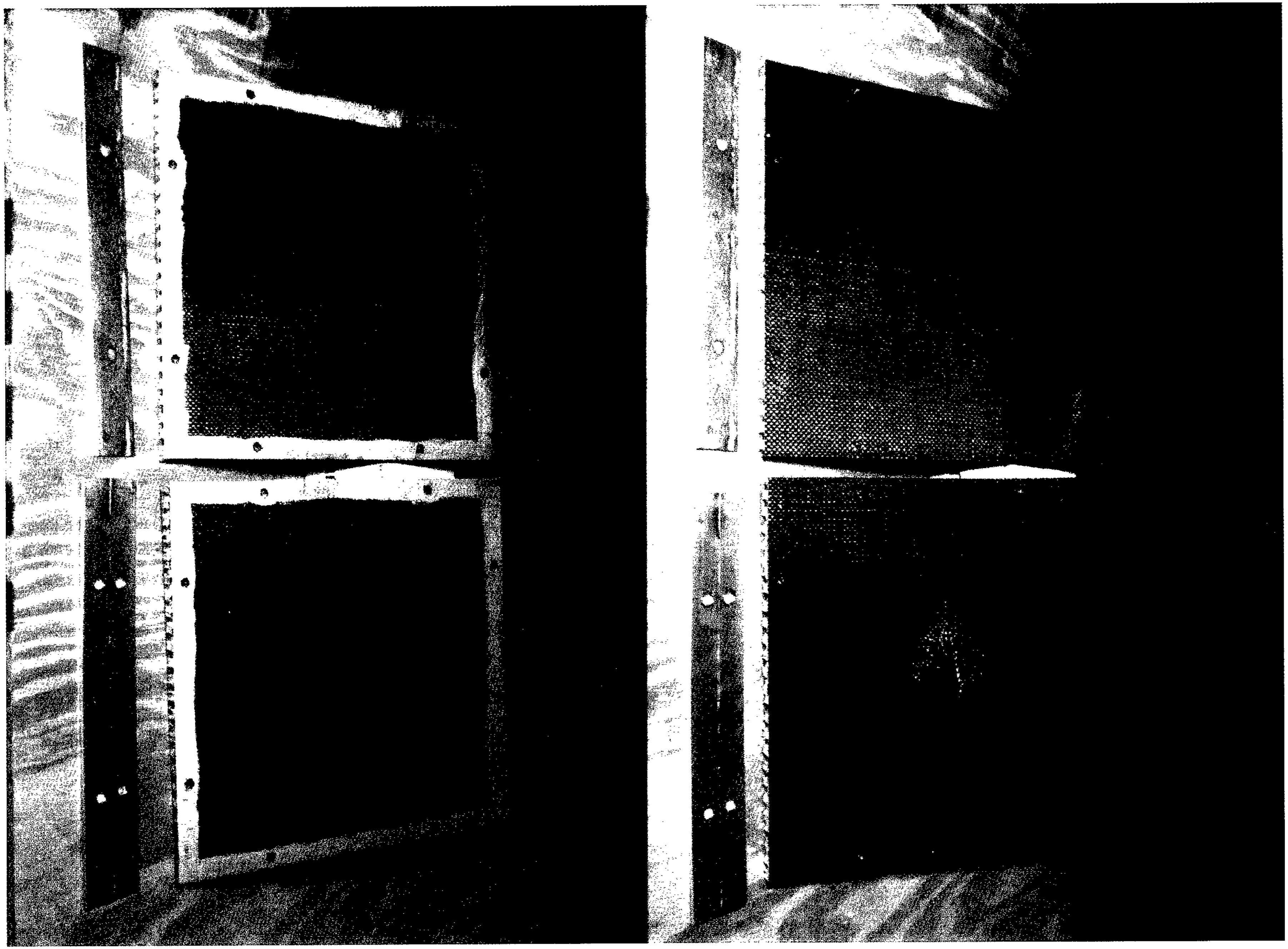


Figure C–1. Direct Strike Damage to Tiles 2a and 2b (Test # 54).

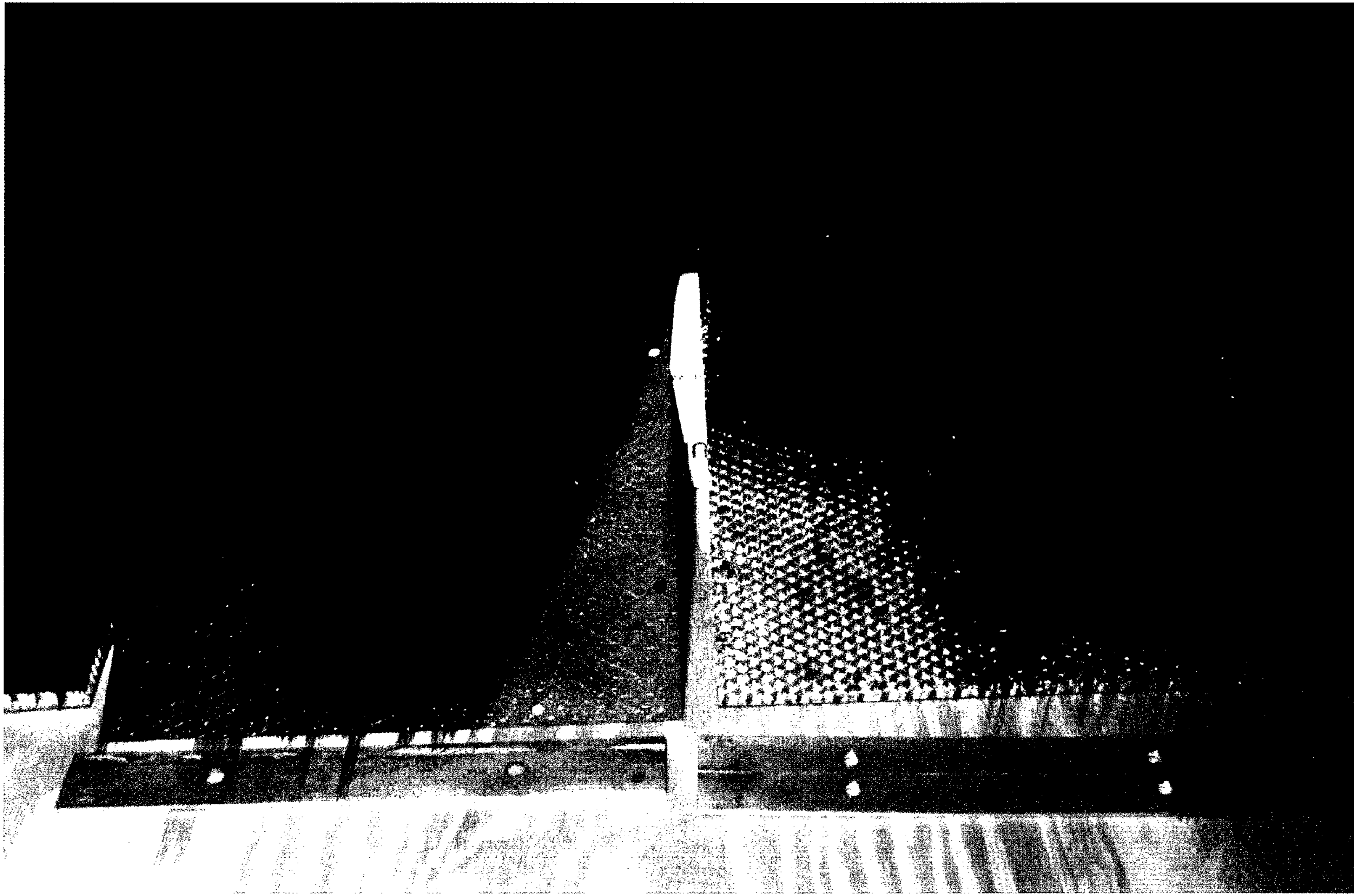


Figure C–2. Separation of Tile 2a (Test # 54).

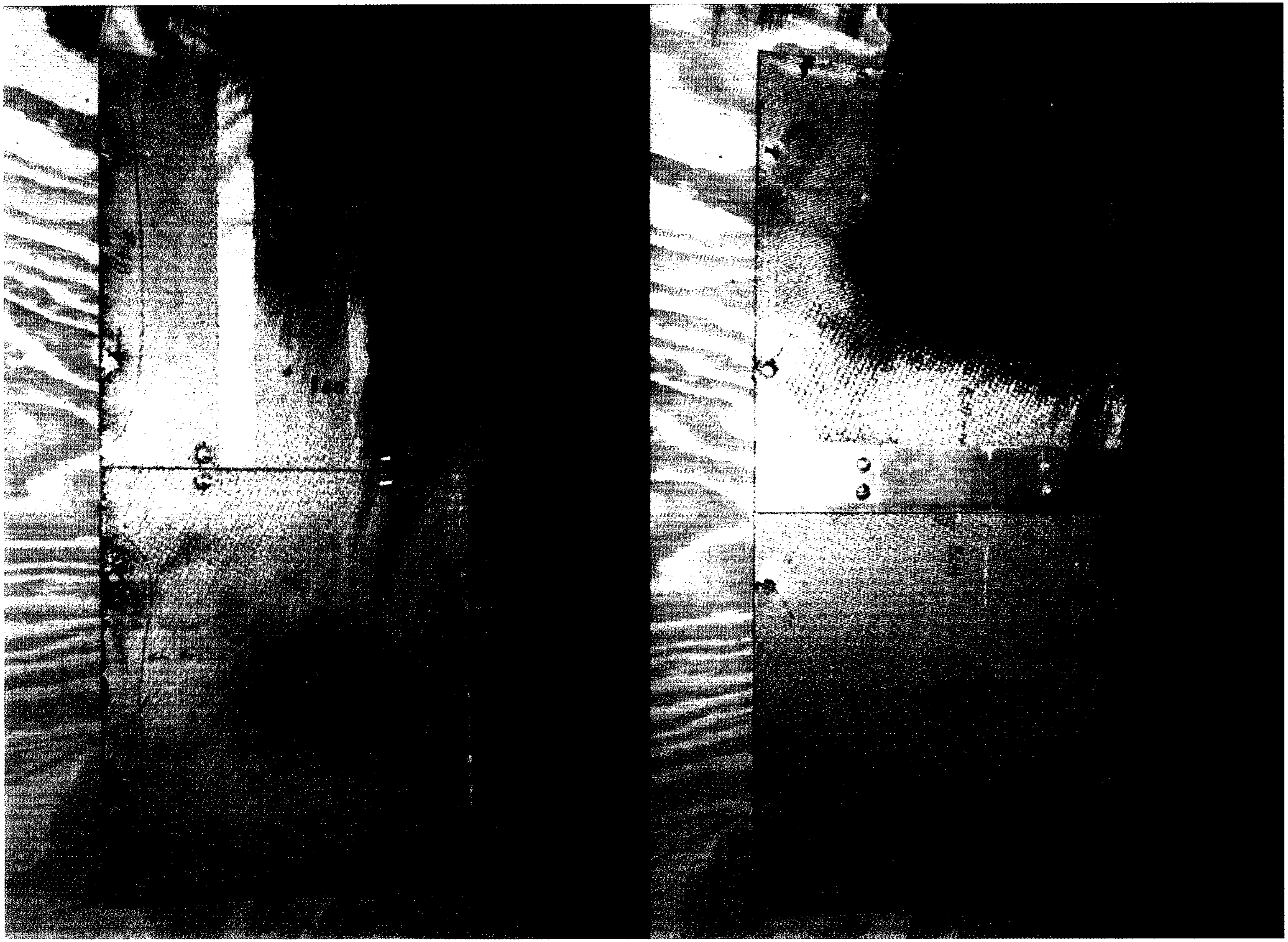


Figure C–3. Direct Strike Damage to Tiles 3a and 3b (Test #55).

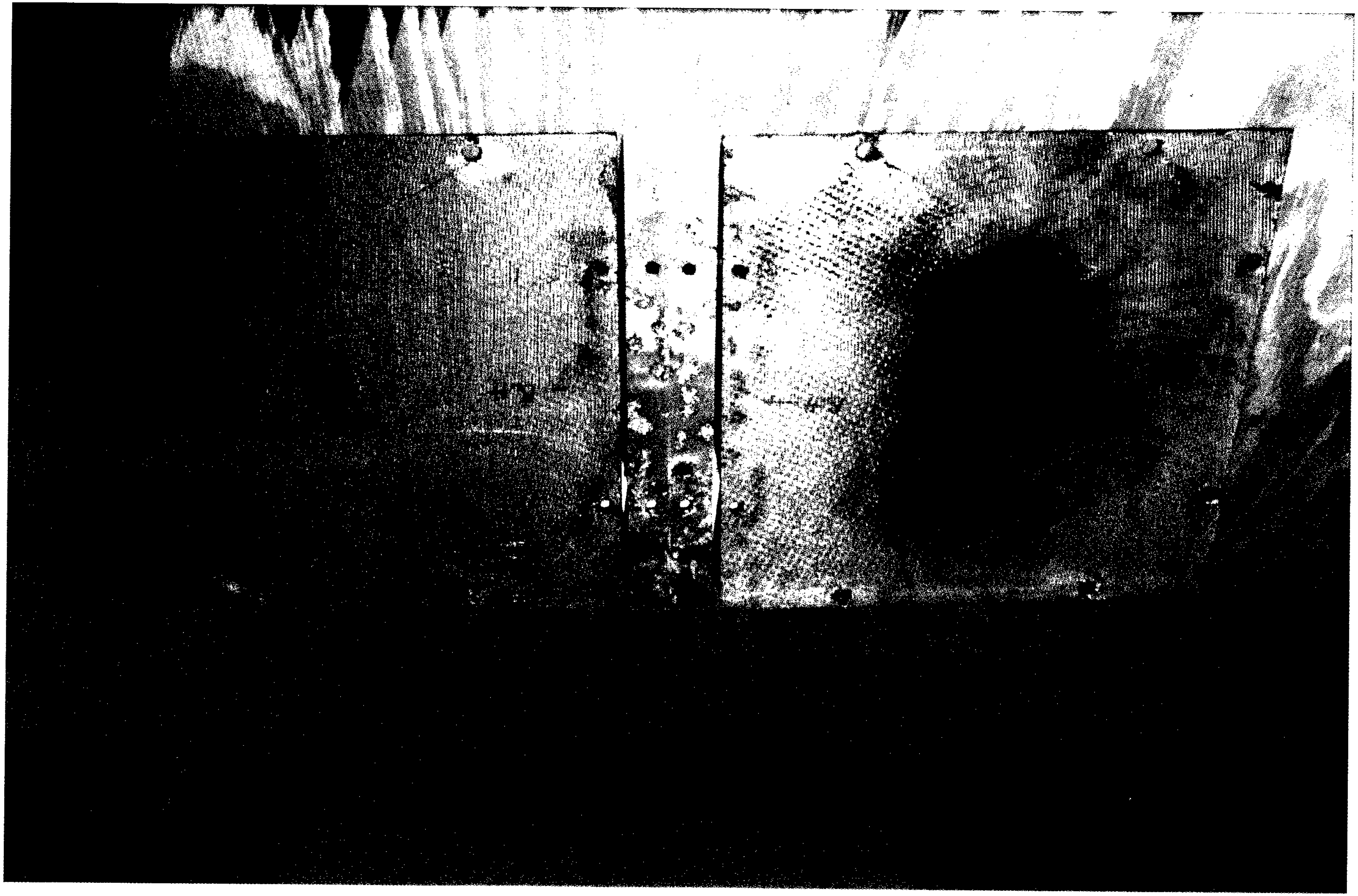


Figure C–4. Joint Damage to Tiles 3a and 3b (Test # 55).

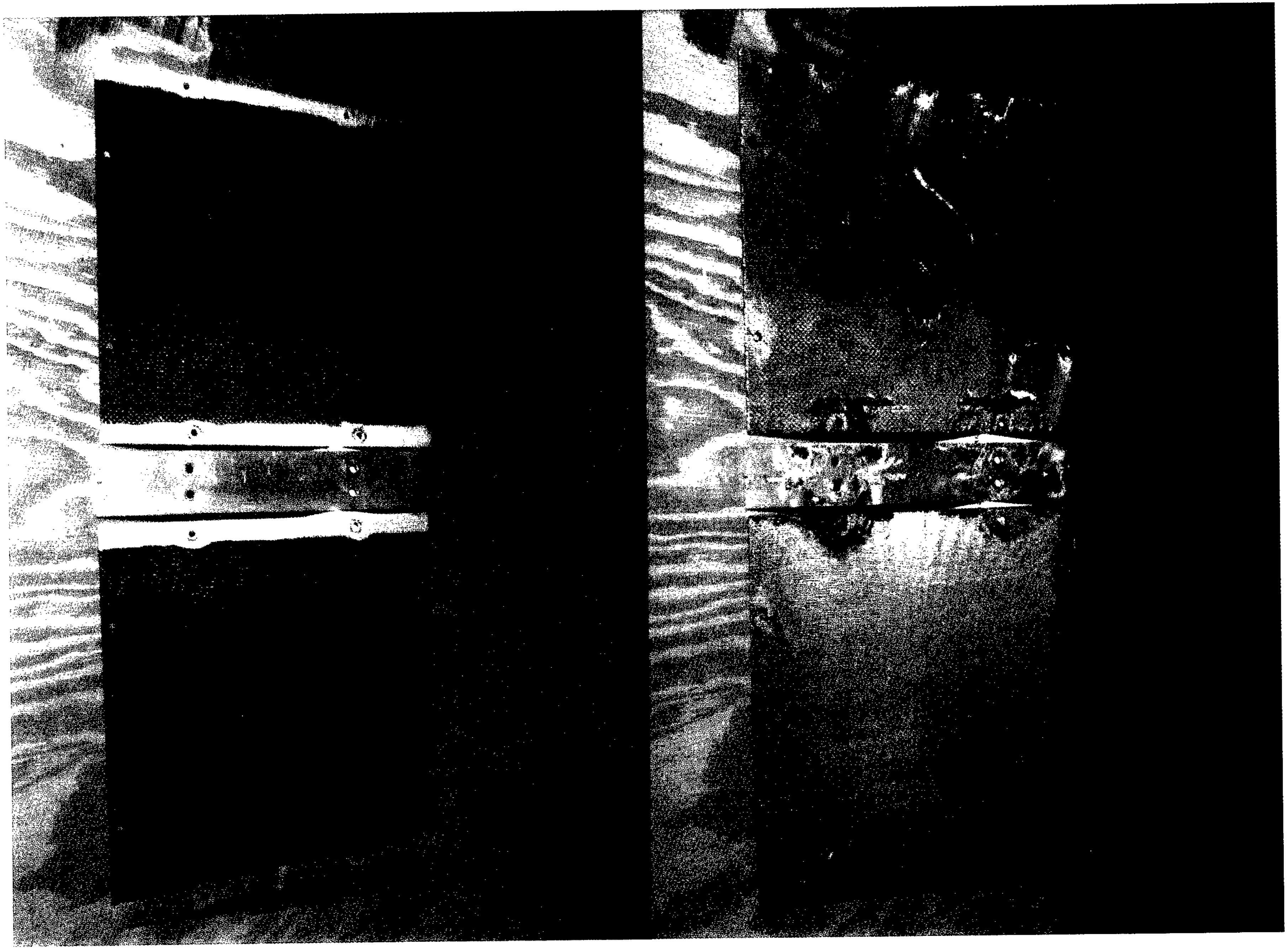


Figure C–5. Direct Damage to Tiles 4e and 4f (Test # 56).

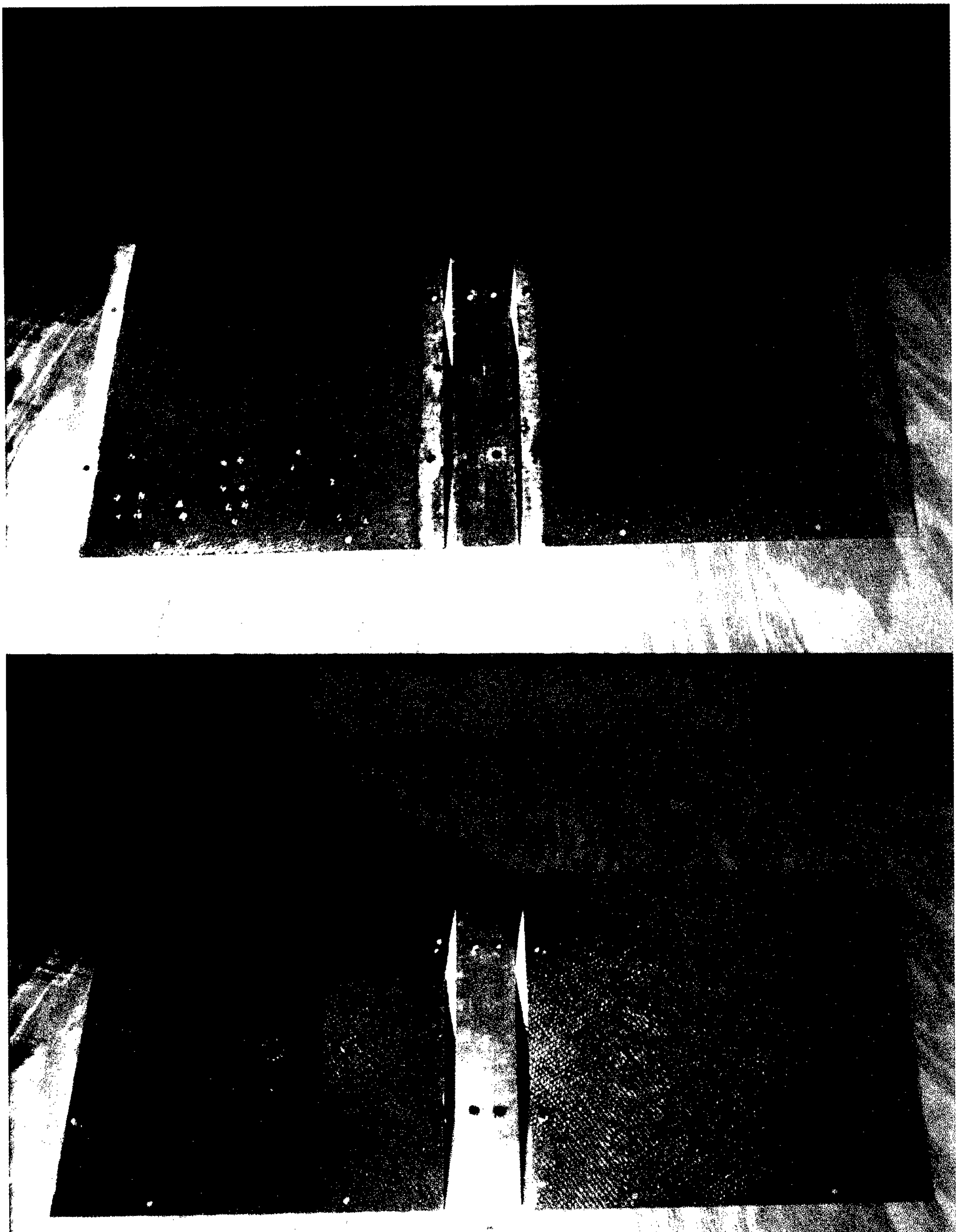


Figure C–6. Direct Strike Damage on Tiles 8e and 8f (Test # 57).

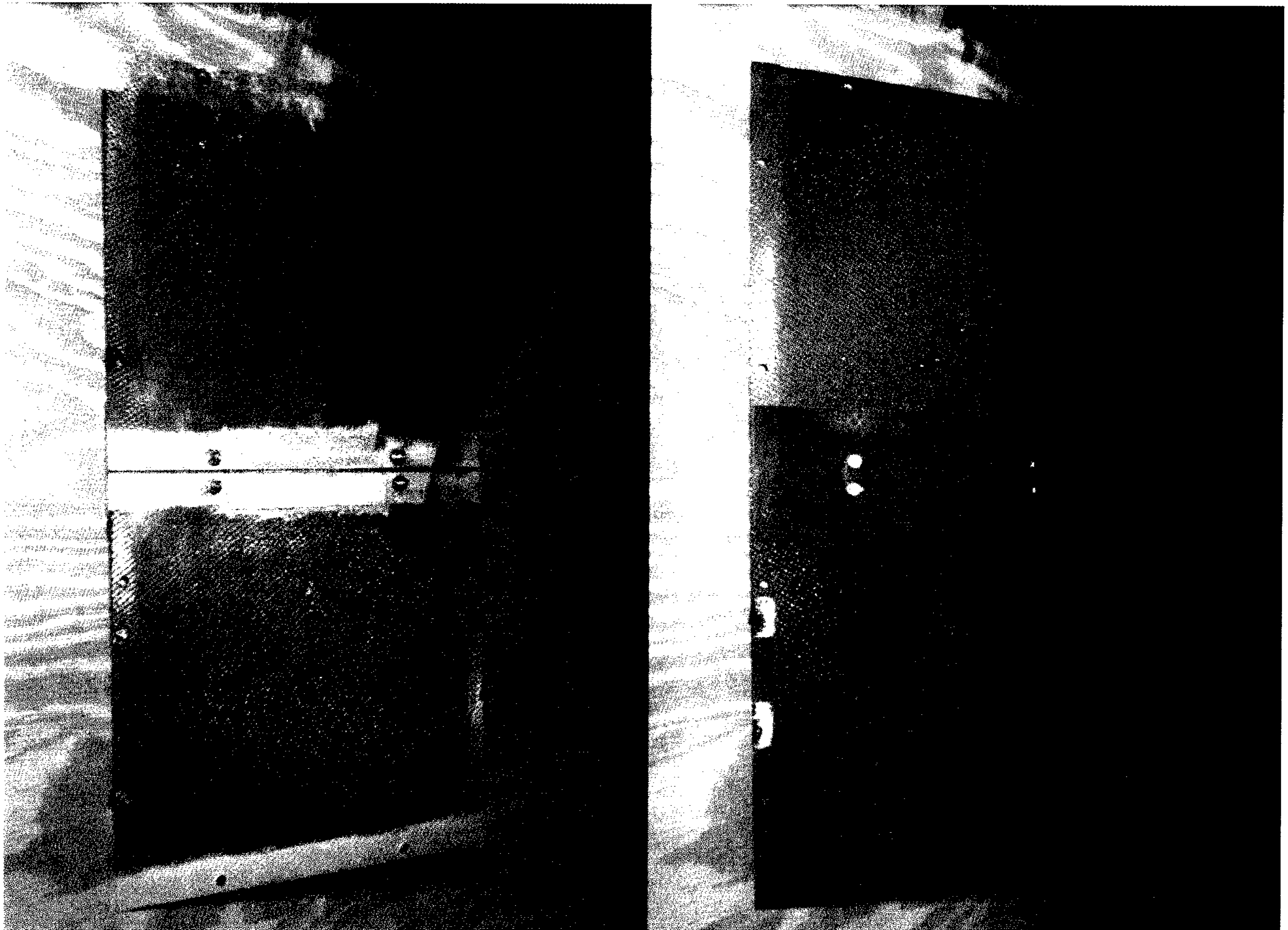


Figure C–7. Direct Strike Damage to Tiles 8g and 8f (Test # 58).

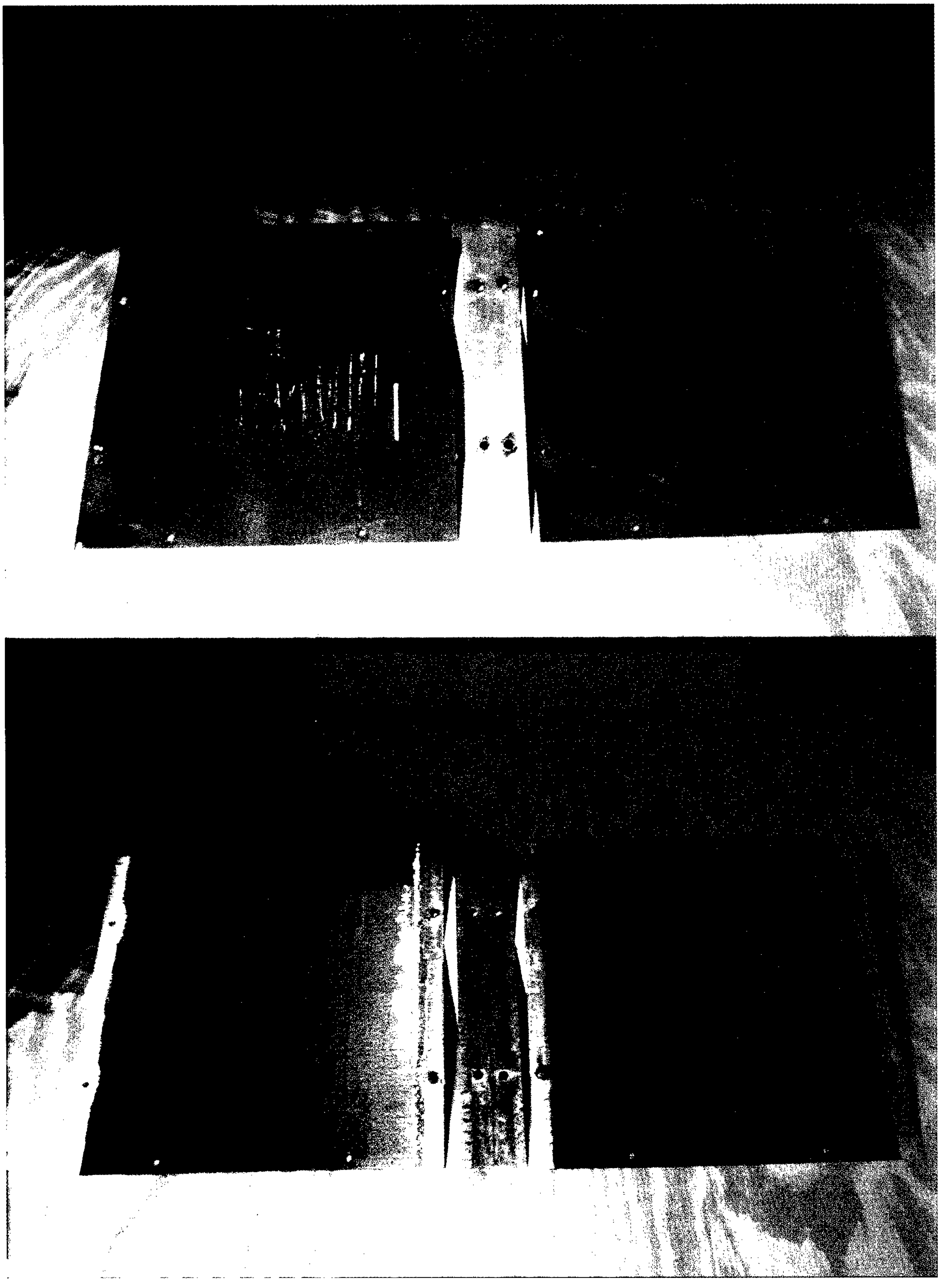


Figure C–8. Direct Strike Damage to Tiles 9e and 9f (Test # 59).

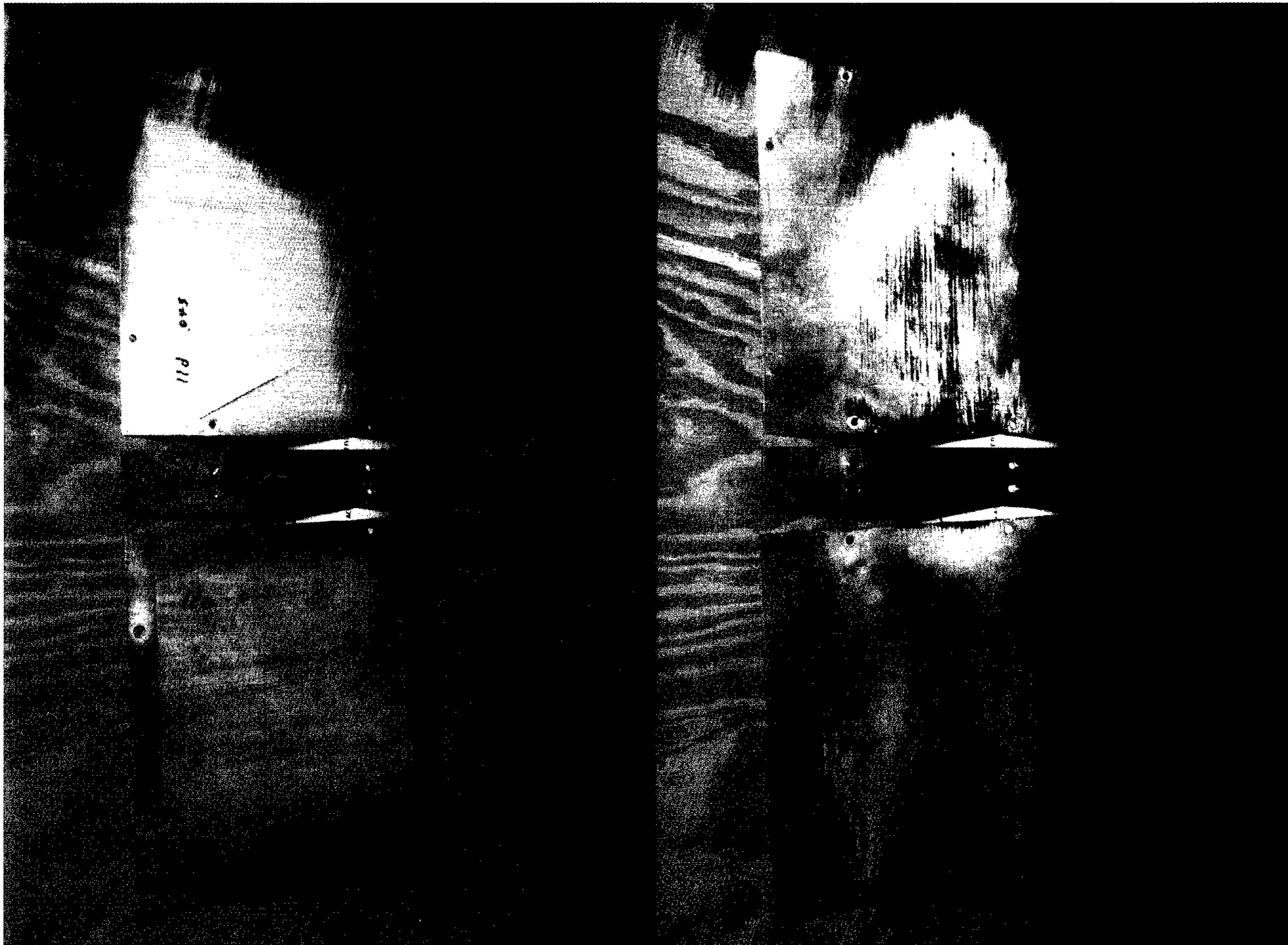


Figure C–9. Direct Strike Damage to Tiles 11c and 11d (Test # 60).

APPENDIX D

Table 1. - Sample Description

SAMPLE TYPE	SAMPLE NO.	DESCRIPTION	MATING SURFACES PAINTED
Aluminum	x	Aluminum plate	
Honeycomb 0.730	1	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers one side, 8 on other; Aluminum core	4
Honeycomb 0.621	2a, b	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers each side; Aluminum core	4
Honeycomb 0.621	2c, d	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers each side; Aluminum core	2
Foil, two sides	3a, b	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers; Expanded Aluminum Foil	0
Foil, one side	4a, b	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers; Expanded Aluminum Foil	4
Foil, one side	4c, d, e, f, g	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers; Expanded Aluminum foil	2
GFRP 0.160	5	Amoco T-300 Fiber; Thiokol TCR Resin; 8 layers	4
GFRP 0.130	6	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers	4
GFRP 0.080	7a, b	Amoco T-300 Fiber; Thiokol TCR Resin; 6 layers	4
GFRP 0.068	8a, b	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers	4
GFRP 0.068	8c, d, e, f	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers	2
GFRP 0.068	8g, h	Hercules IM7 Fiber; Hercules 8552 Resin; 6 layers	2
GFRP Unitape	9a, b	Hercules AS4 Fiber; Hercules 3501 Resin; 6 double layers	4
GFRP Unitape	9c, d, e, f	Hercules AS4 Fiber; Hercules 3501 Resin; 6 double layers	2
GFRP Unitape	9g, h	Hercules AS4 Fiber; Hercules 3501 Resin; 6 double layers	0
Fiberglass 0.060	10a, b, c, d	Airtech Tool Rite; Owens Corning Fiber, Silver Paint Both Sides	0
Fiberglass 0.045	11a, b, c, d	Airtech Tool Rite; Owens Corning Fiber	ALL

APPENDIX E

COMPARISON CALCULATIONS FOR SHIELDING EFFECTIVENESS

The intent of the comparison was to determine the correlation between the shielding effectiveness of the various composite material tiles. The correlation was set up such that a positive value is reflective of higher shielding effectiveness and a negative value is reflective of lower shielding effectiveness. A comparison of the measured values only would not be sufficient since the stimulus environment varied slightly from test to test. Therefore, the comparison had to factor in the slight variations of the stimulus environment.

The correlation was accomplished by multiplying the logarithm to the base 10 of the ratio of the measured sensor responses by 20 and then adding the logarithm to the base 10 of the ratio of the stimulus environments multiplied by 20. This calculation is illustrated in the equation below:

$$SE_{a\text{-}b} = 20 \log (M_b/M_a) + 20 \log (S_a/S_b) \text{ dB}$$

where SE_{ab} is the shielding effectiveness correlation in decibels of sample A to sample B, M_b is the sensor measurement for sample B, M_a is the sensor measurement for sample A, S_a is the stimulus environment upon sample A, and S_b is the stimulus environment upon sample B. An example of the shielding effectiveness calculation is shown for the peak electric field correlation of tile 3B (test #43) to the fiberglass tile (test #41):

Test No.	Sample	Peak Current (kA)	Peak E-Field (V/m)
41	Fiberglass	68	12000.0
43	3B	70	34.4

$$\begin{aligned} SE_{3B\text{-}F} &= 20 \log (12000/34.4) + 20 \log (70/68) \\ &= 20 \log (348.84) + 20 \log (1.03) \\ &= 50.85 + 0.25 \\ &= 51.1 \text{ dB} \end{aligned}$$

It should be noted that the ratios were setup in order to a positive value to be reflective of higher shielding effectiveness and a lower value to be reflective of lower shielding effectiveness.

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Lightning tests were performed on composite materials as a part of an investigation of electromagnetic effects on the materials. Samples were subjected to direct and remote simulated lightning strikes. Samples included various thicknesses of graphite filament reinforced plastic (GFRP), material enhanced by expanded aluminum foil layers, and material with an aluminum honeycomb core. Shielding properties of the material and damage to the sample surfaces and joints were investigated. Adding expanded aluminum foil layers and increasing the thickness of GFRP improves the shielding effectiveness against lightning induced fields and the ability to withstand lightning strikes. A report describing the lightning strike tests performed by the U.S. Army Redstone Technical Test Center, Redstone Arsenal, AL, STERT-TE-E-EM, is included as an appendix.

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